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NATICK/TR-99/004**

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**INTERACTIVE TEXTILES FRONT END ANALYSIS
PHASE 1**

by
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**U.S. ARMY SOLDIER AND BIOLOGICAL CHEMICAL COMMAND
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13. ABSTRACT (Maximum 200 words) A Front End Analysis (FEA) was initiated to identify Interactive Textiles that could be used by the Soldier Systems Center - Natick (SSC-N) for the improvement of Soldier System warfighter materiel. Phase I focused on the Sensate Liner, which is a garment constructed to detect the location of a wound in the torso by means of a conductive fiber grid sewn into a "t-shirt". The garment would, using attached acoustic sensors, also indicate the type and path of the projectile that penetrated the torso. Future Operational Capabilities were reviewed. A survey was developed to collect judgements of combat effectiveness, mission relevance, technical feasibility, and risk criteria. These data were used to arrive at a Figure of Merit (FoM) which was then related to management alternatives. The value of the FoM fell in the "Monitor Program" alternative range. Major conclusions from this analysis were: 1) Future Operational Capabilities support a number of alternatives relating to casualty care and tele-medicine concepts; and 2) The FoM falls into a range of values corresponding to Management actions of monitoring or consulting. Recommendations were: 1) that SSC-N monitor progress of the Sensate Liner project and 2) conduct Phase 2 of the FEA.					
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PREFACE

This report describes an evaluation of the Sensate Liner and summarizes the literature on Interactive Textiles (INEXT). This work was initiated in August, 1997 and completed in March, 1998.

The Sensate Liner was developed as one component in a broader Telemedicine Program sponsored by the Defense Advanced Research Projects Agency (DARPA). The purpose of the program was to improve battlefield triage through the application of telecommunications technologies. The Sensate Liner component was designed to detect and, with a Personal Status Monitor, transmit wound data to approaching medical personnel in order to first attend to those most in need.

A team of experts from the Soldier Systems Center - Natick (SSCN) and the U.S. Army Institute for Environmental Medicine evaluated the Sensate Liner in terms of 5 criteria. These were 1) Combat Effectiveness, 2) Mission Relevance, 3) Cost Risk, 4) Schedule Risk and 5) Technical Feasibility. Evaluations of these factors were used to calculate a Figure of Merit which was then related to alternative management options ranging from ignoring the technologies to actively supporting further development of the technologies involved in the Sensate Liner.

Results of this analysis indicated that management should continue to monitor development of the Sensate Liner concept. It was also recommended that management fund a second phase of the project to expand the methodology to evaluation of other INEXT technologies.

A review of 96 articles in the Defense Technical Information Center revealed 38 references describing materials of potential interest to SBCCOM items.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

A Front End Analysis (FEA) was initiated to review interactive textile technologies and to identify those that could be used by the Soldier Systems Center - Natick (SSCN) for the improvement of Soldier System warfighter materiel. Phase 1 of the FEA focused upon the Sensate Liner (SL), an item developed as a "proof of concept" for improving combat casualty care as part of a Defense Advanced Research Projects Agency (DARPA) tele-medicine program now completed. It is important to keep in mind that focus of this FEA phase pertains to the DARPA program and not to the current Army Warfighter Physiological Status Monitoring efforts. Phase 2 of the FEA plan is to extend the search for, and analysis of, other promising interactive textile technologies with the goal of eventually recommending an SSCN research program in this area.

The Sensate Liner is essentially a garment constructed to detect the location of a wound in the torso by means of a conductive fiber grid sewn into a "t-shirt". The garment would, using attached acoustic sensors, also indicate the type and path of the projectile upon penetration of the torso. With incorporation of a fiber-optic grid, the garment could also detect the amount of blood being lost from the wound. These data would be transmitted by fibers in the garment to a monitor that would process the information and transmit it to remote medical personnel as they travel to the triage area. The technologies involved in the Sensate Liner involve conductive polymers as well as manufacturing technologies. The majority of these technologies are commercially available (in consonance with the "proof of concept" paradigm) with one exception - i.e. a technology for weaving conductive fibers into a garment using conventional weaving equipment.

Technical information on the Sensate Liner (and other interactive textile technologies) was obtained in a literature search. All available information was shared and discussed with a panel of experts drawn from each SSCN former Directorate and the U.S. Army Institute for Environmental Medicine (USARIEM). Future Operational Capabilities as defined in TRADOC PAM 525-66 (TRADOC, June, 1997) were reviewed to select those that might specify a requirement for the Sensate Liner. A survey was developed to collect judgements of the Sensate Liner concept with respect to combat effectiveness, mission relevance, technical feasibility, and risk criteria. Evaluations of these factors were used to arrive at a Figure of Merit (FoM) summarizing the judged value of the Sensate Liner Concept. This value was compared to a categorization of possible management actions and associated values ranging from 0 (ignore the program) to 100 (actively support the program). The value of the FoM fell in the "Monitor" action range.

The following conclusions were drawn from the analysis of Future Operational Capabilities and the technical panel evaluations.

- The military need, as expressed in Future Operational Capabilities, is so broadly stated as to support a number of alternatives relating to casualty care and tele-medicine concepts.

- Support for the Sensate Liner within the Army Medical Research community is difficult to identify.
- The Figure of Merit reflecting evaluations of Mission Relevance, Technical Feasibility, Combat Effectiveness and Risk falls into a range of values corresponding to management actions of monitoring or consulting.

Recommendations were:

- SSCN periodically contact the Sensate Liner project manager to monitor progress.
- Continue to Phase 2 of the FEA.

INTRODUCTION

BACKGROUND Interactive Textiles (INTEXTs) are materials having at least one unique and valuable property that is considered to be "intelligent." That is, the material interacts with the wearer's environment or functions as a conduit linking other items worn, carried or used by the warfighter. An INTEXT material is also multifunctional. For example, a fabric that would respond in real time to the presence of chemical agents (e.g. by swelling and closing the penetration pathways) would be an INTEXT because it responds directly to the environment. Fibers that would expand or contract in response to temperature is also considered to be in interactive textile - one that might be used to provide protection in hot and cold environments with the same garment.. Clothing belts that double as batteries constitute another type of INTEXT.

A distinction can be drawn between INTEXTs as defined above and other related technologies and materials such as wearable computers. The difference is germane to this report in that SSCN has an important area of effort in wearable computers - specifically SSCN's work with DARPA in the development of a Humionics platform for the next generation warfighter: e.g. applications of heads-up displays, computing and reconfigurable micro-robot technologies. These efforts were not reviewed in Phase 1 of this FEA.

PURPOSE The purpose of this FEA is to review interactive textile technologies, select those that may provide improvements in warfighter capabilities, assess the risk and feasibility associated with these more promising technologies and select those that could be pursued to define SSCN's niche in this growth area. In short, the goal of this project is to produce an INTEXT development strategy for integration into the SSCN Science and Technology (S&T) Program. The candidate technologies and materials include (but are not limited to) the following:

- new textile manufacturing technologies;
- advanced fiberoptics;
- conductive, shape-memory, and dendritic polymers;
- sensors and processors;
- gels and other coatings;
- composite materials;
- nano structures (balls, tubes, fibers);
- nano scale sensors and devices;
- Biomimetics;
- micro-robotics;
- piezoelectric materials.

The review was to be conducted in two phases: Phase 1 focused upon technologies involved in the Sensate Liner in order to recommend a course of action with respect to

participating (or not participating) in the development of this program. The Sensate Liner was of particular interest since it is a rather visible effort combining the first four of the above technologies. Phase 2 of the FEA is to extend the analysis to other INTEXT materials, items, or concepts that could reduce battlefield hazards and protect or enhance warfighter capabilities.

This report briefly summarizes Phase 1 of the FEA including results of our Sensate Liner evaluations, literature reviews and identification of relevant in-house efforts currently underway.

ANALYSIS ASSUMPTIONS Several important assumptions were made in conducting our analysis of the Sensate Liner. These were:

- limited SSCN funds could be reprogrammed to support the Sensate Liner prototype development, test, or engineering effort if benefits of the item were sufficiently attractive;
- a clear commercial or non-medical application would be necessary to justify SSCN's support for the program;
- customer survey results from SSCN's Science and Technology Investment Strategy (STIS) review would be widely available;
- technologies used to develop the Sensate Liner may have utility even if not coupled to other tele-medicine items such as the DARPA Personal Status Monitor Proof of Concept prototype.
- technologies necessary to the development and deployment of a Sensate Liner (e.g. data collection and analytical algorithms, DARPA Personal Status Monitor Prototype, telecommunications capabilities, and producibility) can (but not necessarily will) be developed.

Although the first assumption is a monetary consideration, no *a priori* funding level was defined. It was clear, however, that a significant benefit would be required in order to justify reprogramming already scarce resources. The second assumption stems from the fact that the Sensate Liner concept is proposed as an element of an overall Telemedicine initiative under development by the Army medical community and which may not become the responsibility of SSCN or even SBCCOM. STIS customer survey results were assumed to be available since the information would be useful guidance as to SSCN's overall investment strategy. This was an important data element - but not a critical barrier if not available.

The last two assumptions were necessary in order to evaluate the Sensate Liner as a concept separate from the Personal Status Monitor and associated telemetry. Justification for development of the Sensate Liner has been part of a tele-medicine approach to battlefield triage. As such, there is a question of whether the item would become an SBCCOM responsibility. By considering non-medical and non-tele-medicine uses, the evaluation could explore the technologies for more direct application to SBCCOM's

mission. The last assumption is important given that the Sensate Liner was a subsystem of a larger concept.

For the Sensate Liner to function as intended, some type of device is required to monitor and record vital signs. The information must then be analyzed and made available via telecommunication to medical personnel at a remote location. As far as the team was able to ascertain, these Sensate Liner supporting technologies are still in the very early development stage.

PHASE 1: SENSATE LINER EVALUATION

SENSATE LINER BACKGROUND & CONCEPT The Sensate Liner is one component in a tele-medicine system conceived in a DARPA Program initiated in the Biological/Medical Technologies area in fiscal year (FY) 1996. The Program was managed by Col. Richard Satava and executed by Eric Lind of the Navy Command, Control and Ocean Surveillance Center, RDT&E Division (NRaD) as part of the Defense Logistics Agency's Apparel Research Network.

The rationale for development of the concept is that battlefield triage can be improved using telemetry to provide wound and vital signs to medics before they arrive on site. The medics would know, before actually seeing the wounded, which individuals need priority medical attention. It is important to note that the Sensate Liner's functionality is tied directly to other devices to monitor and record physiological data, various data analysis algorithms and telemetry equipment which together would be capable of integrating the wound data with heart rate, blood pressure, and other vital signs and then transmitting the information at specified time intervals to a remote receiver (Lind, et.al., 1997). Our evaluation of the Sensate Liner assumed that some type of physiological status monitor and recorder could, or would, be developed and would function as claimed.

The following two graphics portray several aspects of the Sensate Liner concept. It is important to note that the prototype when developed may differ from the concepts shown below. (Source: <http://web.nt.sainc.com/arpa/abmt/nrad.htm>)

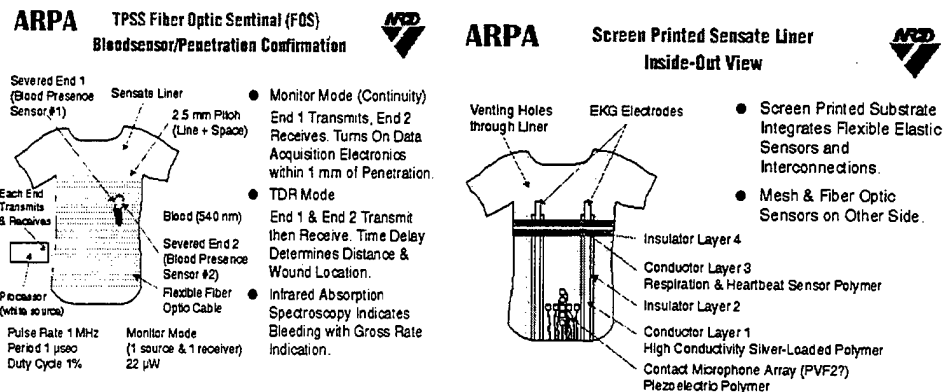


Figure 1: Sensate Liner Concepts

SENSATE LINER MATERIALS AND TECHNOLOGIES

MATERIALS. Mission Research Corporation examined materials related to identification of the type of projectiles that strike the Sensate Liner (R. Eisler, 1997). Specifically, they evaluated an array of slightly overlapping Polyvinylidene Fluoride (PVDF) patches with piezoelectric properties. The patches produce a charge during loading (i.e. when struck by an object) and discharge rapidly upon unloading (i.e. after the object has penetrated the patch). Voltages on the patches are compared continuously to an adjustable trigger threshold. The capability of these patches to detect penetrations by three types of bullets was demonstrated. Active ultrasound and radar were investigated as means to detect the track of projectiles and acoustic signatures were obtained using ordnance gelatin.

ILC Dover's task in the Sensate Liner program was to "establish viable conductive thread systems for integration with panel or liner systems and to establish methods to interface threads to one another and to other bio-sensor devices" (Anon, 1996; G. Baird, January, 1997). All of the threads evaluated by ILC Dover were commercially available. Three silver coated Nylon threads were tested for electrical and physical properties and found to have electrical properties that would meet the Sensate Liner program goals for ballistic penetration detection and interface to other sensor components. Three carbon filament threads and carbon loaded conductive epoxies were also evaluated and found to not meet Sensate Liner requirements; i.e. too fragile and -excessively high electrical resistance. Thread insulation systems were also evaluated and Teflon® coatings with high temperature binder systems were considered not acceptable. Tests were apparently conducted with lower temperature Teflon cure systems and Polyolefin coating systems, but results were not available in published reports obtained for this FEA.

With but one exception (silicone rubber fiberoptic threads), materials examined by the Georgia Institute of Technology were also commercially available items (S. Jayaraman, January 1997). Meraklon yarn and a microdenier polyester/cotton blend yarn were selected for evaluation in terms of comfort criteria and for the base garment. Silica-based fiberoptic, plastic fiberoptic and silicone rubber fiberoptic fibers were reviewed for penetration sensor application with the plastic being chosen for further experimentation. The silica based optic fiber was not selected in part because the glass fibers splintered and could be dangerous if they enter the bloodstream. The silicone rubber optical fiber was not used, because of its large diameter and it was not commercially available at the time required. To construct the "elastic printed circuit board" feature of the Sensate Liner, doped inorganic fibers with a polyethylene or nylon sheath and thin copper wires with a polyethylene sheath were selected over intrinsically conductive polymers for further study for construction of a Sensate Liner prototype.

MANUFACTURING TECHNOLOGIES. ILC Dover employed conventional embroidery technology in their production of a Sensate Liner prototype. The Georgia Institute of Technology examined knitting and weaving technologies to produce their prototype garment and have applied for a patent covering their approach to weaving the

above materials using conventional machinery. The prototype produced by weaving does not have sleeves. This difference becomes important in some of SSCN's possible applications.

SENSATE LINER REQUIREMENTS REVIEW

FUTURE OPERATIONAL CAPABILITIES. TRADOC PAM 525-66; *Future Operational Capabilities* (FOCs) was reviewed to identify those FOCs, if any, that support the Sensate Liner concept. Appendix A presents the list of potentially relevant FOCs.

Only one FOC specifically contained the word "tele-medicine". MD 97-002: *Medical Command, Control, Communication, Computers, and Intelligence (MC4I)* calls for the "capability to provide tele-medicine enablers at all echelons". Also, it states that "...MC4I communication, information, and automation systems must have the ability to: determine patient accountability; track patient movement in all echelons; regulate patients into and out of theater hospitals; manage, coordinate, and assess the theater Class VIII system; and access patient conditions". References to casualty care occur in TR 97-038 and Branch FOCs.

Near real-time casualty reporting is required in TR 97-031: *Sustainment Services*. Assuming that the relevant tele-medicine data collection, analysis and reporting algorithms needed to make the Sensate Liner function as intended were proved, the requirement in this FOC would be exceeded. This appears to be still an unproved assumption.

The statement requiring "tele-medicine enablers" at all echelons could be used as the basis for further development of the Sensate Liner prototype. Bear in mind that the DARPA Sensate Liner is a "proof of concept", and is not intended to be the best technical approach. The need for tele-medicine as well as improved capabilities for triage and casualty identification, reporting or tracking could be addressed by alternative concepts such as the Personal Area Network being developed by T.G. Zimmerman and IBM among other researchers (Zimmerman, 1996).

SENSATE LINER TECHNOLOGY ROUNDTABLE. In August 1997, a roundtable session was called by Dr. Eric Lind and chaired by Mr. Jim Parkinson from the Stanford Research Institute. The participants included a number of individuals from industry. The purpose of this gathering was to explore potential users of the Sensate Liner technology and to explore alternatives for the scope and direction of the near term technology development effort. One individual, a former Army Medical Corpsman, expressed his reservation concerning the need for the Sensate Liner. Other applications were presented. For example current space suits, which astronauts criticized because of the many sensors that had to be attached to the garment. Sensate Liner technology could possibly be developed to incorporate the sensors into the garment rather than being

attachments. Firefighters might also benefit from a garment that could monitor their vital signs and warn of impending danger from heat stress or a garment that could transmit the firefighter's location in smoke-filled buildings. The results of these discussions were to be in a White Paper on the Sensate Liner. (To date, it has not been published.)

SENSATE LINER TECHNOLOGY EVALUATION

TEAM COMPOSITION. The first step in evaluating Sensate Liner technologies was to construct a team of experts from SSCN science and commodity Directorates as well as the U. S. Army Research Institute of Environmental Medicine. The team members are identified in Figure 2. In addition, Major Mark Washechek supported the team as its military representative.

MEMBER	ORGANIZATION
Paul Leitch	S&TD
Tom Tassinari	SurD
Carole Winterhalter	SurD
James Fairney	SurD
Jean Herbert	S&TD
Norm Roberts	SusD
Calvin Lee	MobD
Reed Hoyt	USARIEM

Figure 2: Members of the Sensate Liner Evaluation Team

MANAGEMENT OPTIONS. One of the team's earliest actions was to identify various management alternatives with respect to the Sensate Liner program. Five basic options were identified ranging, in terms of degrees of support, from Sponsoring to Ignoring the program as it is proposed and as it evolves.

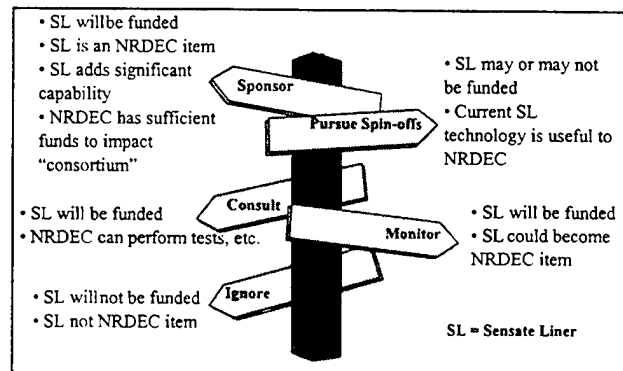


Figure 3: Management Options and Considerations with Respect to the Sensate Liner Proposed Program

Four conditions were identified as necessary for SSCN sponsorship of the Sensate Liner Program: that the program would be funded by others, that it would become an item more closely aligned to an SSCN product area, that it would add significant capability to the warfighter and that SSCN would have sufficient funds to impact the program or to influence a consortium constructed to pursue the technology. At the other extreme, if the Sensate Liner program were to become unfunded or if it remained solely a component of a proposed tele-medicine system, then SSCN should ignore the program. The conditions necessary for SSCN sponsorship were intentionally more stringent than conditions for other options in recognition of the fact that S&T funds are limited.

The middle range of management options ranges from Monitoring to the Pursuit of Spin-offs. If after this evaluation it appears that the Sensate Liner will be developed and becomes an SSCN item, it is in the Center's best interest to at least monitor the program. Monitoring could lead to either collaborative or consultative relationships, which is the next level of activity called Consult. This level depends, of course, upon program needs

and the RDEC's capability or willingness to perform tests, conduct technology assessments, or otherwise dedicate some resources for a short period of time. Monitoring and/or Consultation could also lead to identification and pursuit of spin-offs if this FEA or subsequent developments uncover technologies of sufficient application to SSCN programs at some level of investment and control that would be desirable to initiate.

EVALUATION APPROACH

The approach to evaluating the Sensate Liner involved five major activities: collect and review all available relevant reports; develop evaluation criteria; develop an assessment survey; analyze results and draw conclusions.

COLLECT AND REVIEW REPORTS. The team reviewed several articles, contractor reports and presentations describing the Sensate Liner. Since not all team members were equally aware of the materials, several sessions were held to assure that each member understood the documentation and technologies related to the Sensate Liner.

DEFINE EVALUATION CRITERIA AND FIGURE OF MERIT. Five factors were examined in order to arrive at an overall assessment of the Sensate Liner.

Combat Effectiveness (CE) is the degree to which a combat outcome is influenced by addition of the associated capability. In this case the combat outcome would be some reduction in the percentage of warfighters killed in action, which could be attributed to the capability of providing more effective triage. The capability claimed for the Sensate Liner and related components is the early identification of - and thus attention to - the most critically wounded which in turn permits more effective triage.

Mission Relevance (MR) is the extent to which the technology addresses - or could be made to address - SSCN's mission areas as identified in the STIS documentation. With respect to Sensate Liner technologies, the more pertinent areas are Individual and Collective Protection as well as Precision Aerial Delivery.

Technology risk was broken into two components: one reflecting cost and the other reflecting schedule uncertainty. Cost risk (TR_C) is the "chance" that the projected unit cost of the technology/item will be achieved given a specific availability date. The higher the chance the cost will be achieved in a given time frame, the lower the cost risk. In this case, the Sensate Liner Developer stated (anon. in Bobbin, January, 1998) that the unit cost would be between \$25 and \$35. Schedule Risk (TR_S) is the "chance" that the technology/item will be available, at a given cost, by a specified date. Schedule risks must carefully consider MANPRINT requirements (e.g. comfort,) and technology challenges - e.g. durability, producibility.

Technology Feasibility (TF) was defined as the likelihood that the technical approach and technology being developed would result in the claimed capability enhancements.

Evaluations of this factor also must consider whether claims for the technology are consistent with known physical laws and relationships.

These factors were combined in an additive model as follows:

$$\text{Figure of Merit} = (CE + MR + .5(TR_C + TR_S) + TF) / 4$$

where: CE = Combat Effectiveness
MR = Mission Relevance
TR_C = Technology Cost Risk
TR_S = Technology Schedule Risk
TF = Technical Feasibility

Note that the two technology risk factors have been averaged together. This was done so that risk would not receive more weight than any other single factor. No differential weights were assigned to the other factors (CE, MR, TF).

ADMINISTER SENSATE LINER TECHNOLOGY EVALUATION SURVEY.

Each team member completed the two page survey forms included in Appendix B of this report. The first page of each survey described either the ILC Dover prototype or the Georgia Tech prototype. Other information was contained on this page and was intended to describe the current wound treatment capability. The information included data on the types of wounds, a narrative description of the Sensate Liner concept and the new capability it would provide followed by the proposed cost and expected year the item would be available.

The second page of the survey was identical and asked respondents to assign points from 0 to 100 for each factor. For Combat Effectiveness, Mission Relevance and Technical Feasibility, the respondent simply assigned a number from 0 to 100 reflecting the degree to which the Sensate Liner met each of these criteria. If it were judged to provide a significant new capability thus enhancing combat effectiveness, or if it were judged to be highly relevant to one or more of SSCN's business areas, or if it were judged to be technically feasible in the near term, the points assigned would be near 100 for each factor.

The format for evaluations of technical cost and schedule risk differed from that used for the other three factors. To establish a cost risk factor, points were distributed among a range of costs (from <\$10 to >\$81) with the year of availability held constant (2001). The average of the points assigned to the cost range of \$21 - \$40 was used to estimate the cost risk factor. The same procedure was used to assess schedule risk: i.e. years were varied from 1998 to 2003 in one-year increments while cost was specified to be \$35. A simpler procedure could have been used, such as assigning 0 to 100 points to a specific cost or year. However, by specifying ranges for each risk factor and by distributing points within each range, an expected cost and availability date could be computed for the Sensate Liner. This could become important information if results were to support SSCN's active involvement in the program.

SENSATE LINER SURVEY RESULTS

Results of the team members' evaluations are presented in Figure 3. Medians and Inter-Quartile Ranges were selected as the measures of central tendency and dispersion because the sample size in this case was small and the observations were not normally distributed. The Inter-Quartile Range as well as the Median is displayed for each factor by the bars and horizontal line respectively. The low end of the bar indicates the point value corresponding to the 25th percentile while the high end represents the value of the 75th percentile.

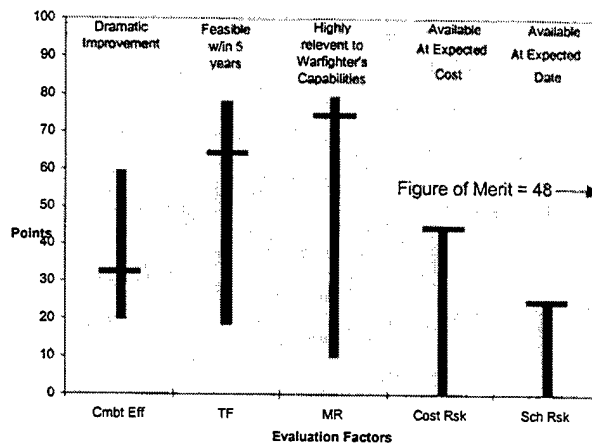


Figure 4: Figure of Merit and Components of the Sensate Liner Technology Evaluations

Mission Relevance and Technical Feasibility were evaluated rather highly in terms of the median of the team members' ratings. Combat Effectiveness was, as indicated by the median of the assessments, judged to be of lesser importance and there was less certainty that the item's cost and availability would be \$35 in five years. The number for each factor is the average (median) of the evaluations assigned to the factor and is indicated by the solid horizontal line. It is important to bear in mind that there was a substantial amount of variability among individuals as reflected by the inter quartile ranges associated with ratings of each factor (shown by the bars in Figure 3). The medians for Combat Effectiveness, Technical Feasibility, Mission Relevance, Cost and Technical Risks are 33, 65, 75, 45, 25, respectively. Employing the formula described earlier, the Figure of Merit (FoM) is 48 (out of a possible 100).

FIGURE OF MERIT and MANAGEMENT OPTIONS

A range of the Figure of Merit (FoM) related to the management options defined earlier was established and is presented in Figure 4. Although the divisions were established arbitrarily rather than empirically, they reflect the notion that there should be relatively narrow bands with respect to either of the extreme actions (Sponsor or Ignore), and a fairly broad band for the Monitor and Consult actions so as to keep abreast of a variety of new technologies. The observed Figure of Merit for Sensate Liner and associated technologies is 48 - a level that puts it in the middle range of management options. The most closely associated options are to Monitor and Consult.

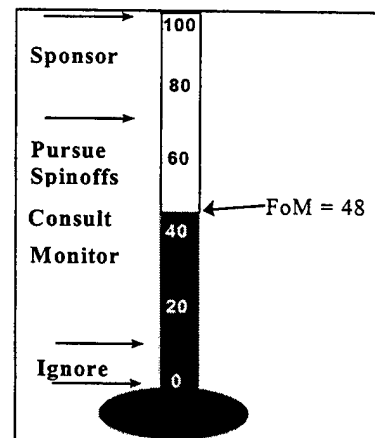


Figure 5: Figure of Merit and Possible Management Actions

CONCLUSIONS - SENSATE LINER

The following conclusions are drawn from the data presented.

- The military need, as expressed in Future Operational Capabilities, is so broadly stated as to support a number of alternatives relating to casualty care and tele-medicine concepts.
- Support for the Sensate Liner within the Army Medical Research community is difficult to identify.
- The Figure of Merit, reflecting evaluations of Mission Relevance, Technical Feasibility, Combat Effectiveness and Risk, falls into a range of values corresponding to management actions of monitoring or consulting.
- The majority of the materials and manufacturing methods proposed for producing the Sensate Liner are commercially available at the present time.
- The Sensate Liner concept is being aggressively marketed as evidence by reviews in the popular press as well as at technical forums.

OTHER PHASE 1 PRODUCTS

WARRIOR SYSTEMS SBIR PROPOSALS

Information generated in the Sensate Liner program has lead to the development of an SBIR proposal solicitation involving electro optic fabric concepts: i.e. OSD98-003: *Electro Optic Fabric Concepts for Combat Clothing*. The objective of this solicitation is to integrate a conductive electronic/optical network within prototype garments constructed from wearable fabric(s). Contracts will be awarded to four small businesses to investigate both polymer and textile material developments. Further information on this and four related SBIR solicitations can be found on the Internet at: http://www.nttc.edu/solicitations2/current/dod_sbir981/osd.txt. The titles and technologies of the related SBIR topics are:

- OSD98-001 TITLE: Light Weight Warrior Protective Enclosures
TECHNOLOGY: Textile Technology
- OSD98-002 TITLE: Multi-threat Protective Uniform System
TECHNOLOGY: Multi-functional Textile Materials, Uniform Systems
- OSD98-004 TITLE: Elastomeric Perm-Selective Materials for Chemical Biological (CB) Protective Clothing.
TECHNOLOGY: Membrane Textile Technology
- OSD98-007 TITLE: Polymer Electrolyte Batteries
TECHNOLOGY: Polymer Science, Electrochemistry

MOBILITY SBIR PROPOSAL

Based upon the materials reviewed in Phase 1, a new SBIR proposal was developed. The essence of that proposal is to develop experimental methods based on fiber optics technology to measure stress and strain of parachute canopy fabrics. Currently, there are no satisfactory methods to monitor the dynamic stress levels of a parachute canopy during inflation. These stress levels are critical to know in terms of maintaining the structural integrity of the canopy. This proposal was among the five proposals, selected from nineteen SBIR proposals, that were forwarded to and approved by Army Materiel Command.

LITERATURE SEARCH RESULTS

Based upon the Defense Technical Information Center (DTIC) literature search generated at the start of this FEA, a list of projects that reported developing or evaluating a smart material was compiled. Projects that summarized broad programs or that did not reference a specific material were excluded from the list. Figure 6 (pages 12-15) presents these projects. Ninety-six references were provided by this search, 38 of which met the above selection criteria. The projects are presented in order from the most recent to the earliest. The older projects (those completed in FY93) are still of interest since, in Phase 2 of this FEA, we will determine what, if anything, transitioned from these efforts and whether the application could be tailored to SSCN items even if developed for another purpose. Vibration and sound deadening 6.1 work, for example, may have been accomplished in support of helicopter requirements - but may also now have utility for reducing the noise of Combat Service Support field equipment items or for "quieting" the interior of SSCN shelters. The entries in shaded boxes refer to the material described in the project summaries presented in Appendix C. The project officer and total funding are also shown to the right of each materiel entry. Where two dollar amounts are shown, the greatest reflects the total program expenditures and the smaller amount identifies the dollars spent after Fiscal Year 1993.

The level of funding for these projects ranges from as little as \$11K to over \$2M with the majority (56%) in the \$200K to \$400K range. To some degree, this supports the validity of an assumption that SSCN does not have the resources to exert a major influence on the direction of this type of research - our funds are too small in comparison to what is spent by most other players.

One observation that may be drawn from this search is that, where specific applications were cited, chemical/biological defense and rotary wing vibration damping appear to dominate the thrust of these research efforts. Only a few of the projects cited an application of direct and obvious application to Soldier System items. However, as noted above, some of this basic work on sound deadening and vibration damping may have application in such shelter programs as the Standardized Integrated Command Post System - even though the problem of interest to the researchers involved rotary wing aircraft.

Prior Fiscal Years	FY 1994	FY 1995	FY 1996	FY 1997	
				Lyotropic gel coatings	H. L. Schreuder-Gibson; NRDEC/S&TD; \$11K
				Mesoscale (1um-1mm) Piezoelectric shell transducers and Piezocomposite hydrophones	I. Aksay; Princeton Univ; \$2,563K
				Ultra thin Langmuir-Blodgett films (based upon Azobenzene Dyes) with photoswitchable properties	J. T. Koberstein; Connecticut Univ; \$192K
				Matallacarborane Sandwich Complexes	R. N. Grimes; Virginia Univ; \$245K
				AMOCO High Conductivity Graphite Fabric	J. Connolly; 603 TAC Sqdm, \$218K
			Melt Spun Piezoelectric fibers		G. P. Sendeky; Wright R&DC, W-P AFB; \$80K
			Unique polymer coating technique		W. Muller; NRDEC/S&TD; \$40K
Pulsed Electron Beam Fabrication of Smart Materials			Pulsed Electron Beam Fabrication of Smart Materials (2)		F. M. Mako; FM Technologies Inc.; \$393K (FY96) F. M. Mako; FM Technologies Inc.; \$100K (FY93)
			Active acoustic coatings		C. R. Fuller; Virginia Polytechnic Inst; \$471K - \$784K
			Electrorheological Fluids and Piezoelectric materials		K. W. Wang; Penn State Univ; \$194K - \$254K
			Smart Materials Structures & Embedded Sensors of Intelligent Process and Adhesives Monitoring		D. J. Inman; Virginia Polytechnic Inst.; \$1884K

Figure 6: Smart Materials Research (6.1) Literature Summary

Prior Fiscal Years	FY 1994	FY 1995	FY 1996	FY 1997
Cultured Cells on Smart Materials Substrates				
Alternative Polymer layers with Hi & Low Nonlinear Optical Indices & equal nonlinear index of refraction				G. G. Wallace, Wollongong Univ; \$70K - \$120K
Fiber Optics with Dye coated polymers				Y. Zhao; Wayne State Univ; \$240K - \$360K
Polymer Gel Sensors				M. L. Myrick; South Carolina Univ; \$260K - \$387K
Ferroelastic-Ferroelectric Heterostructures				Z. Hu; Univ of Texas; \$93K - \$152K
Ionic Polymeric Gels				I. Parise; State Univ of New York; \$164K - \$252K
Visco-Elastic damping layers between Piezoelectric layers				M. Shahinpoor; New Mexico Univ; \$206K - \$310K
Flexible silvered Polyester sheet with embedded fine wires				A. M. Baz; Catholic University of America; \$206K - \$304K
Ordered Assemblies of DNA & Protein with polymeric LB Monolayer Systems				T. C. Corke; Illinois Inst of Tech; \$300K - \$450K
				K. A. Marx; Univ of Mass Lowell; \$116K - \$626K

Figure 6: Smart Materials Research (6.1) Literature Summary (Cont)

FY93 and Prior	FY 1994 to Present	
Analysis & Optimization of Elastic Materials	Further Development Applications???	R. Rostamian; Maryland Univ; \$300K
Novel Electro Polymers	Further Development Applications???	E. Mintz; Atlanta Univ Center Inc; \$335K I. Kahn; Clark Atlanta Univ;
Damage-survivable Laminated Composites with Piezoelectric layers	Further Development Applications???	S. P. Joshi; Texas University - Arlington Aero; \$371K
Ultrafast Frequency Agile Optical Materials (Gels)	Further Development Applications???	E.L. Chronister; California Univ - Riverside; \$255K
Smart Electromagnetic Structures	Further Development Applications???	M. H. Thursby; Florida Inst of Tech - Space Res Inst; \$420
Electrorheological Fluids	Further Development Applications???	M.T. Shaw; Connecticut University - Storrs Chem Eng; \$164K
Nitinol-reinforced Smart Composites	Further Development Applications???	A. M. Baz; Catholic University MEng; \$374
Amphiphilic generated non-hexagonal LB Films	Further Development Applications???	C. J. Eckhardt; Nebraska Univ Chem Dept; \$500K
Molecular-Responsive Organic Materials	Further Development Applications???	A. D. Hamilton; Pittsburgh Univ Chem Dept; \$426K

Figure 6: Smart Materials Research (6.1) Literature Summary (Cont)

FY93 and Prior	FY 1994 to Present	
Novel Switchable Protein Surfaces	Further Development Applications???	R. K. Gilpin; Kent State; \$420K
Shape Memory Alloy Controllers	Further Development Applications???	V. S. Rao; Missouri University - Rolla; \$329K
Mica Layer Structured Actuators	Further Development Applications???	L. Cartz; Marquette Univ; \$294K
Laminated Composite Structures with embedded fiber optic & hybrid actuation/sensing Capabilities	Further Development Applications???	B. S. Thompson, M. V. Ghandi; Michigan State Univ; \$350K
Blepharismun Visual Pigment Protein	Further Development Applications???	P. Song; Univ of Nebraska; \$275K
Smart Piezothermoelastic Laminates	Further Development Applications???	H. S. Tzou; Univ of Kentucky; \$374K
Self Assembled Lipid Bilayers	Further Development Applications???	H. T. Tien; Michigan State Univ; \$345K
Piezoelectric film on Intercalated Carbon Fiber Thread	Further Development Applications???	N. Shaikh; Nebraska Univ; \$162K R. Dillon; Nebraska Univ Engineering (Mech) Dept.
Nano Scale Gold Wires on GAAS Substrate	Further Development Applications???	J. E. Fumaux; Oklahoma Univ; \$435K

Figure 6: Smart Materials Research (6.1) Literature Summary (Cont)

It should be noted that nearly all of these projects were funded through the Army Research Office and are being executed by academia. It is also important to note that our search did not uncover references to wearable computers, although it was expected that this work would be found with keywords such as smart materials. However, this also suggests that the two bodies of literature are fairly distinct - at least as far as the DTIC database is concerned.

PHASE 1: RECOMMENDATIONS

Based upon the observations and conclusions stated above, the following recommendations are offered.

- Monitor the Sensate Liner program by periodic contacts with the principal investigator, Eric Lind and the major contractors, Georgia Institute of Technology, ILC Dover and Mission Research Corporation.
- Complete Phase 2 of the FEA by obtaining more information on the materials identified in Phase 1 and developing potential SSCN applications for subsequent evaluation.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-99/004 in a series of reports approved for publication.

APPENDIX A

Applicable Future Operational Capabilities.

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APPENDIX A

Applicable Future Operational Capabilities.

MD 97-002. Medical Command, Control, Communication, Computers, and Intelligence (MC4I)

TR 97-038. Casualty Care, Patient Treatment and Area Support. Description: The Army requires the capability for level I and II medical treatment and Area Support. Rapid casualty location and application of improved treatment modules will provide focus toward reducing the historically recalcitrant killed-in-action (KIA) rate. The capability requires improved methods of physiological resuscitation, improved diagnostic and treatment capabilities at both unit and area-level treatment facilities. All health care providers will require advance trauma management training and sustainment training and organizations must provide communications between providers and mentors to optimize reductions in the KIA rate. Medical personnel require the ability to treat patients under all conditions and require night vision capability. CHS providers require the ability to initiate and continue casualty treatment under nuclear, biological, and chemical (NBC) conditions. The combat medic will require improved ability to function while in individual protective gear. All forward deployed medical modules will require collective medical protection to ensure continued patient care under NBC conditions. NBC casualties will require improved methods of rapid decontamination and emergency treatment followed by protection and continued medical management to ensure survival. Digitized patient records, beginning prior to deployment and continuing throughout casualty management are required to ensure seamless medical treatment. Automated read/write devices and data base software for medical status, patient tracking and reconstitution are required for use before, during, and after operations to ensure soldier readiness for combat and to allow timely transmission of location and status to health providers, commander's, and family members. Capability to track casualty emergency ministrations and pastoral care information to data collection points for use by casualty assistance offices and notification of NOK. Capability would provide notification officers and accompanying chaplains with vital battlefield pastoral care information.

Branch FOC. CH 97-002; CM 97-004, CM 97-006; MD 97-003.

CM 97-004. NBC Collective Protection.

Description: Capability to provide safe and effective collective protection for personnel and equipment from all standard and nonstandard NBC hazards. Must provide mobile, fixed site, and vehicle crew protection; must be readily decontaminated/ self decontaminating; have integrated and regenerative power supply and air handling capability; and has internal environmental control (heating, cooling, humidity). Must provide flexible, METT-T tailorable protection. Must maximize protective and storage life and minimize dedicated /specialized logistics, personnel, or training. Must be compatible with all combat environments, equipment, communications, and camouflage.

References: TRADOC Pam 525-5, p. 3-18, paragraph 3-3b(1)(d); p. 4-8, paragraph 4e(2)(c)7; TRADOC Pam 525-20; TRADOC Pam 525-63, p.7, paragraph 3-2c(2).

Previous OCR: EEL08.

CM 97- 006. NBC Medical Defense.

Description: Capability to effectively treat and pretreat soldiers to minimize chemical/ biological (CB) and residual radiological effects on soldiers. Must provide a single multivalent pretreatment and treatment for all CB agents and residual radiological effects. Must reduce/eliminate significant adverse collateral medical attention or operationally degrading effects.

References: TRADOC 525-63, p. 7, paragraph. 3 -2c(1)(b),(c); p. 8, paragraph 3-2e(1); paragraph A 9b.

MD 97-003. Patient Treatment and Area Support.

Description: Required Capability for level I and II Medical Treatment and Area Support is rapid casualty location and application of improved treatment modalities which will provide focus on reducing the historically recalcitrant killed in action (KIA) rate. Improved methods of physiological resuscitation, improved diagnostic and treatment capabilities at unit-level and area-level treatment facilities are required. All health care providers will require advanced trauma management training and sustainment training, and organizations must provide assured communications between providers and mentors to optimize reductions in the KIA rate. Medics require the ability to treat casualties under all light conditions. Especially, combat medics at both levels I and II require night vision capability. CHS providers require the ability to initiate and continue casualty treatment under NBC conditions. The combat medic will require improved ability to function while in individual protective gear. All forward deployed medical modules will require collective medical protection to ensure continued patient care under NBC conditions. NBC casualties will require improved methods of rapid decontamination and emergency treatment followed by protection and continued medical management to ensure survival. Digitized patient health records, beginning before deployment and continuing throughout casualty management, are required to ensure seamless medical treatment. Automated, read/write devices and database software for medical status and patient tracking are required for use before deployment to ensure soldier readiness for combat and to allow timely transmission of location and status to health providers, commanders, and family members.

Reference: TRADOC Pam 525-50, paragraph 2-2d., paragraph 2-3d(1)(2), paragraph 2-3e.

Previous OCR: CSS07.

31. TR 97-031. Sustainment Services. Description: Capability to execute and manage all personnel-related matters and contribute to the morale and welfare of the soldier in the field by providing the most benefit to the maximum number of personnel. Will provide near real time strength accounting, replacement operations, religious support/Pastoral care operations, medical support operations, casualty reporting, finance services, postal services, morale support activities, and legal services. These services share equal importance with the requirement for availability of materiel on the battlefield.

Branch FOC. AD 97-010; AR 97-002, AR 97-008, AR 97-012; AV 97-009, AV 97-010; BCL 97-003, BCL 97-009; CS 97-001; CH 97-011; CM 97-005; CS 97-003, CS 97-004; DSA 97-018; EN 97-014, EN 97-015, EN 97-019, EN 97-020; FA 97-016, FA 97-030, FA 97-031; FI 97-003, FI 97-004, FI 97-005, FI 97-006, FI 97-008; IS 97-001; MD 97-001, MD 97-003, MD 97-004, MD 97-005, MD 97-006, MD 97-007, MD 97-008, MD 97-009, MD 97-010, MD 97-011, MD 97-012; MP 97-015, MP 97-016; OD 97-001, OD 97-003, OD 97-004, OD 97-005, OD 97-006, OD 97-007, OD 97-008, OD 97-014, OD 97-016, OD 97-017; QM 97-001, QM 97-002, QM 97-003, QM 97-004, QM 97-005, QM 97-006, QM 97-007, QM 97-008, QM 97-009, QM 97-011; SP 97-001, SP 97-002, SP 97-003, SP 97-004, SP 97-005, SP 97-006, SP 97-007, SP 97-008, SP 97-009, SP 97-010, SP 97-012, SP 97-013, SP 97-014, SP 97-015, SP 97-016, SP 97-017, SP 97-019, SP 97-020; TC 97-001, TC 97-002.

APPENDIX B
Sensate Liner Surveys

APPENDIX B: Sensate Liner Surveys

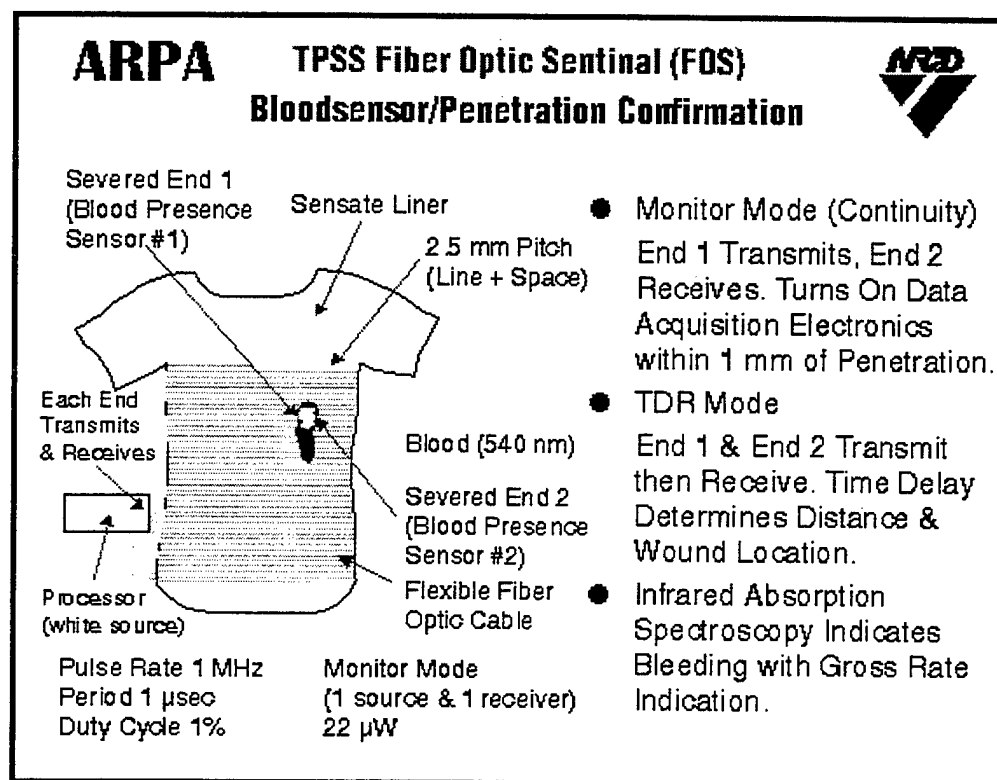
SENSATE LINER TECHNOLOGY ILC Dover Prototype

Current Battlefield Capability: Wounded warfighters are evacuated from the area of the firefight and receive treatment in a forward medical facility. Historically, the distribution of hits by body region is as follows:

Body Region	Major Wars	Vietnam
Head	12%	15%
Chest & Abdomen	27%	23%
Upper Extremities	22%	18%
Lower Extremities	39%	44%

Source: Wound Ballistics Casualty Office, OTSG, Wash. DC

Narrative Description: The Sensate Liner technology can produce an undergarment by stitching flexible fiber optic threads and conductive polymer threads (which can be attached to acoustic sensors) using conventional commercial manufacturing equipment and methods.



New Capability: Medical personnel will be able to attend to the most critically wounded more quickly since they will know, via an electronic transmission, which of the wounded need immediate attention and, with GPS, will also know where they are located in the battlezone. Assume in this evaluation that the required telemetry will be ready.

Cost Estimate: The estimated cost of the Sensate Liner is \$25 to \$30 per garment (including sensors and processor but excluding transmitter and power supply).

Available: The year in which the Sensate Liner could be issued to warfighters will be 2001.

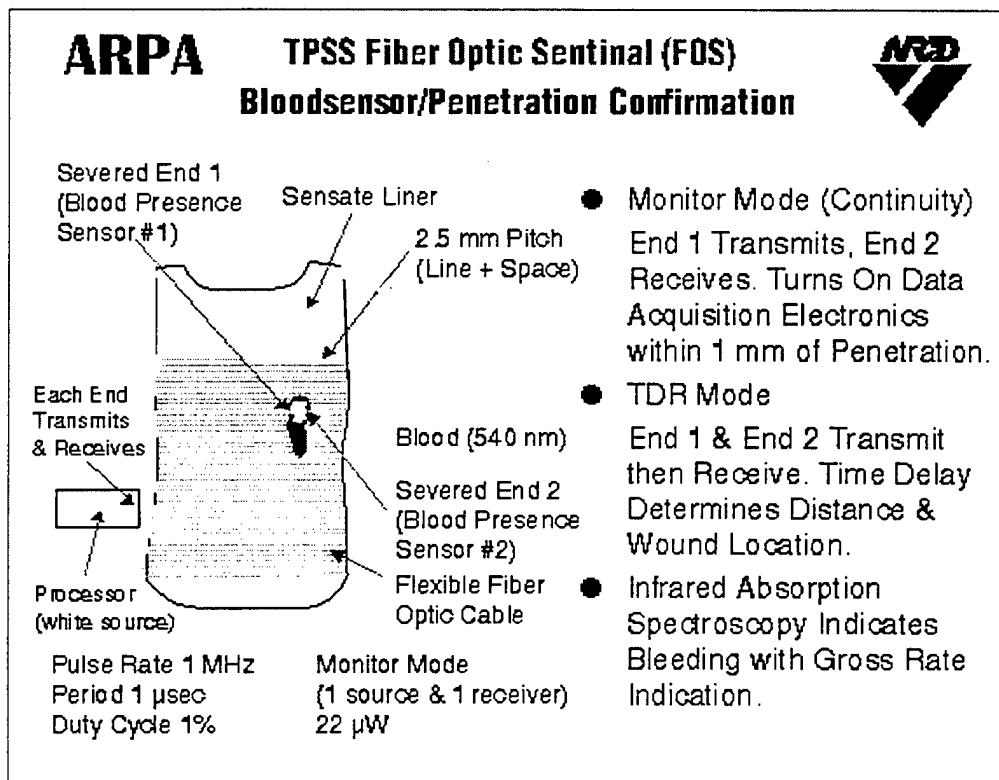
SENSATE LINER TECHNOLOGY Georgia Tech Prototype

Current Battlefield Capability: Wounded warfighters are evacuated from the area of the firefight and receive treatment in a forward medical facility. Historically, the distribution of hits by body region is as follows:

Body Region	Major Wars	Vietnam
Head	12%	15%
Chest & Abdomen	27%	23%
Upper Extremities	22%	18%
Lower Extremities	39%	44%

Source: Wound Ballistics Casualty Office, OTSG, Wash. DC

Narrative Description: The Sensate Liner technology can produce an undergarment by weaving plastic flexible fiber optic threads and conductive polymer threads (which can be attached to acoustic sensors) using conventional commercial manufacturing equipment and methods.



New Capability: Medical personnel will be able to attend to the most critically wounded more quickly since they will know, via an electronic transmission, which of the wounded need immediate attention and, with GPS, will also know where they are located in the battlezone. Assume in this evaluation that the required telemetry will be ready.

Cost Estimate: The estimated cost of the Sensate Liner is \$25 to \$30 per garment (including sensors and processor but excluding transmitter and power supply).

Available: The year in which the Sensate Liner could be issued to warfighters will be 2001.

TECHNOLOGY EVALUATION SURVEY

Georgia Tech Sensate Liner

BACKGROUND: The claims made by the developer are based on the following assertions and vision. In spite of advanced evacuation capabilities the mortality in the zone of close combat has remained 90% over the centuries. Modern technology may make it possible to reduce mortality at the front lines and regain that "golden hour" (the majority of deaths occur within 60 minutes of the wound) for the soldier by placing emphasis upon sending the surgeon back to the front lines in real time with telepresence. The first premise is that we can continuously monitor the individual soldier and know when an injury has occurred, the severity of the injury and where the soldier is located (PERSONAL STATUS MONITORING) through remote sensing technology (the Sensate Liner suite). The second premise is that the medic can have access immediately to a remote physician who can advise and mentor the medic (TELEMONITORING). Other premises involve TELEPRESENCE SURGERY, TELECONSULTATION, VIRTUAL REALITY MEDICAL SIMULATION AND MEDICAL INFORMATICS in a GLOBAL GRID

TECHNOLOGY ASSESSMENT

COMBAT EFFECTIVENESS EVALUATION: _____ assign a number from 0 to 100 indicating the extent to which you judge that the sensate liner would improve our current capability to locate and give appropriate treatment to the wounded. If your assessment is that there would be no improvement over current capability, then allocate 0 points. If you believe that we could achieve dramatic improvement you would allocate as much as 100 points.

TECHNOLOGY COST RISK

Please place **a number from 0 to 100** indicating the degree to which you believe the item would be available **at each cost** by 2001.

Unit Cost Range	Percent Chance
<\$10	
\$11-\$20	
\$21-\$40	
\$41-\$60	
\$61-\$80	
>\$81	

TECHNOLOGY SCHEDULE RISK

Please place a **number from 0 to 100** indicating the degree to which you believe the item would be available for \$35 **in each of the indicated years**.

Year When Available	Percent Chance
1998	
1999	
2000	
2001	
2002	
2003	

TECHNICAL FEASIBILITY _____ assign a number from 0 to 100 indicating the extent to which you judge the underlying technology to produce this item to be feasible within the next 5 years.

MISSION RELEVANCE: _____ assign a number from 0 to 100 indicating the extent to which you judge this item to be within NRDEC's mission to foster technologies that enhance the individual warfighter's capabilities (i.e. Survivability, Sustainability, Mobility, Lethality, C3I,

APPENDIX C

Smart Material Literature Search References

APPENDIX C

Smart Material Literature Search References

Smart Gel Coatings for Water and POL Resistant Fabric

Principle Investigator: H. L. Schreuder-Gibson

SSCOM/NRDEC/S&TD

DD 1498 Work Unit Summary: 2/4/97

OBJECTIVE: Smart gel-coatings will be investigated for application to fabrics for water and petroleum oil and lubricant (POL) protection. Provide fabric protection to penetration of liquid without reducing moisture vapor transport, that is, provide water and chemical protection without increased heat stress. APPROACH: Develop heterogeneous multilayer barriers with new lyotropic gels that are commercially available. These are smart gels that swell over 1000 times their original volume upon contact with liquid. Construct a hydrophilic/hydrophobic against a hydrophobic/hydrophilic layered system to provide resistance to both polar and nonpolar challenges. Measure the effect of layered construction and gel swelling upon the transport of moisture vapor and heat through the fabric system. PROGRESS: None to report.

Materials Systems Through Mesoscale Patterning

Principle Investigator: I. Aksay

Princeton University

DD 1498 Work Unit Summary: 3/17/97

OBJECTIVE: To develop the next generation of active smart structural systems based on miniaturization of the subsystems (actuators, sensors, and microprocessors) in the internal structure, by focusing on mesoscale (1 μm to 1mm) material processing and fabrication. APPROACH: The first task will develop the synthesis and fabrication techniques to fabricate smart organic/inorganic mesoscale composites by; (i) extension of laser stereo-lithography techniques, (ii) microfabrication by self assembled monolayers and (iii) self assembly of 3-D structures. The second task will be to develop two smart structural material systems. (i) the first will use mesoscale piezoelectric shell transducers to generate large displacements and sustain moderate forces. (ii) the second system will explore the use of matrices with negative Poisson's ratio in order to design and fabricate highly sensitive 1-3 piezocomposite-hydrophones at the mesoscale. It is anticipated that this research will lead to sensors and actuators that are sufficiently small so that they can be readily integrated into microelectronics and micromechanical systems. By using these miniature units as building blocks, one can also produce smart material systems that can be used at larger length such as smart structural components. PROGRESS: None to report.

Molecular Engineering and Smart Polymer Surfaces

Principle Investigator: J. T. Koberstein

Connecticut University

DD 1498 Work Unit Summary: 1/8/97

OBJECTIVE: To understand and design smart polymer systems that have light switchable surface conformations. APPROACH: 1. The research would synthesize ultrathin Langmuir-Blodgett films (from photoactive materials based upon azobenzene dyes) with photoswitchable surface properties. 2. Surface pressure-area isotherms will be measured in both cis and trans states in order to understand the effects of spacer length, end group length, side group type and concentration on the dye orientation and packing. 3. Orientation changes will be characterized via grazing incidence-reflection infrared spectroscopy and surface chemical structure will be studied by xps and surface tensiometry (dynamic contact analysis). 4. Develop design potentialities of a wide range of nanostructures that are potentially suitable for future microsensor and smart material devices. PROGRESS: None to report.

Designed Synthesis and Assembly of Molecular Building Blocks for New Materials

Principle Investigator: R. N. Grimes

Virginia University

DD 1498 Work Unit Summary: 12/20/96

OBJECTIVE: The designed synthesis and assembly of molecular building-blocks for new materials. APPROACH: Development of rational synthetic routes to new families of electroactive, magnetoactive, and/or optically active materials. The main synthons, or building blocks, in this work are small

metallacarborane sandwich complexes that exhibit high thermal and oxidative stability, chemical versatility, electronic tunability, and solubility in organic solvents. The project entails the synthesis of molecular precursor compounds, their assembly into polymeric or solid state materials, and detailed investigation of selected systems with respect to their electronic structure, magnetic behavior, and nonlinear optical properties. Previously developed methods for the preparation and derivatization of small metallacarborane sandwiches will be employed to synthesize and tailor the molecular building blocks, and a variety of physical methods including multinuclear NMR, infrared UV-visible, and ESR spectroscopy, x-ray crystallography, electrochemical techniques, electrical conductivity, and magnetic susceptibility measurements will be employed in their characterization. PROGRESS: None to report.

Improved Processing for Field Level Repair

Principle Investigator: J. Connolly

Tactical Air Control Center Squadron (603rd) APO

DD 1498 Work Unit Summary: 6/16/97

OBJECTIVE: With the increasing amounts of both advanced composites and adhesive bonded structures in the Air Force inventory, there will be a dramatic increase in the number of on-aircraft bonded repairs made to these structures. Conventional bonded repairs are normally effected by applying heat and pressure to the area to be repaired in order to cure the repair adhesive or prepreg material. Composite materials require specified amounts of heat and pressure in order to attain maximum strength. A current limitation to existing equipment is the large temperature gradient across the repair area because of substructure, and uneven heating by the heat blanket. The objective of this program is to utilize or develop promising heat blanket concepts to reduce temperature variations in the repair area in order to achieve high quality on-aircraft repairs to composite structures. **APPROACH:** Vought has proposed a low risk low cost solution to the problem of uneven heating of the repair area during composite repairs. When these repairs are accomplished using existing heat blankets it is not uncommon to see a temperature variation of 50 degrees or more across the repair area. Vought's approach incorporates **high conductivity graphite fabric** with high temperature packaging materials to produce a flexible, durable, low maintenance system easily implemented in the U. S. Air Force's field-level repair activities. The system will be very simple to use in field service requiring only that the system be placed in the repair area between the heat blanket and the release plies of the repair. The system equalizes the repair area temperature distribution by using the graphite fabric as a thermal diffuser. The graphite fabric conducts heat energy from hot spot to cold spots on the repair surface because of its high conductivity. **PROGRESS:** (19 Jan 95 to 28 Jun 96) We are currently at about midpoint in Vought's technical efforts on this contract. Vought has fabricated several examples of their heat distribution system from AMOCO's high conductivity graphite fabric. Several different thicknesses and fiber orientations have been tested. Two different thermally complex test panels have been used to evaluate the system's performance. One being aluminum; the other graphite epoxy. Testing to date has shown that the heat distribution system has significantly reduced the temperature variations across the test area to + or - 17 degrees F. Vought is currently making other modifications to the system to try to achieve the program's goal of + or - 10 degrees f

Unique Polymer Coating Technique Selectively Permeated for Personal Protection

Principle Investigator: W. S. Muller

SSCOM/NRDEC/S&TD

DD 1498 Work Unit Summary: 10/22/96

OBJECTIVE: To explore protective barriers based on "active" or "smart membrane system which function in a similar fashion to cell membranes by regulating the passage of materials through its walls. In the proposed system we would incorporate specific pore-forming materials into barrier materials. These pores would be gated and when the gates are open the materials containing the pores are able to freely pass moisture vapor. Upon exposure to a threat, such as chemical or biological agents, the gates can be designed to shut upon triggering, thus providing the needed protection until the threat passes. **APPROACH:** The principal pore materials currently under study are self-assembling protein based pores. The advantage of these materials are they are very well characterized, they form pores of consistent controllable size, and they can be bioengineered with triggers, receptors, enzymes and related materials to form the basis of the gates. These pores are under study for their ability to integrate into films of other polymeric materials to form mechanically stable materials for evaluation of moisture vapor transmission rates and gas permeation rates using chemical agent simulants. Some triggers have already been designed into these materials which

respond to metal ions and light, demonstrating the feasibility of this approach. We would be engineering the pore forming materials to optimize their incorporation into membranes and to couple triggers to them. PROGRESS: The Langmuir-Blodgett (LB) technique was used to incorporate pore-forming proteins into various lipid and protein matrices. At a constant pressure the pore-forming protein when added to the subphase of the LB trough, in the presence of a stable monolayer, there was a significant increase in the area of the isotherm recorded over time. Such an increase in area is an indication of incorporation. However microscopic techniques have yet to identify the incorporated pore-forming protein in a matrix. Conducting polymers are being studied as a possible membrane system to incorporate these pore-forming proteins. A **unique polymer coating technique** has been employed to successfully coat fabric material used in military uniforms.

Smart Structures Using Novel spun Piezoelectric Fibers

Principle Investigator: G. P. Sendeckyj

Wright Research & Development Center, Wright-Patterson AFB

DD 1498 Work Unit Summary: 6/16/97

OBJECTIVE: Develop novel melt spun technology piezoelectric fibers for smart structures

application: APPROACH: 11 Mar 96 - New Start. PROGRESS: New Start.

Pulsed electron Beam Fabrication of Smart Materials

Principle Investigator: F. M. Mako

FM Technologies Inc.

DD 1498 Work Unit Summary: 5/13/97

OBJECTIVE: The objective of this research effort is to demonstrate the feasibility of fabricating a smart material containing layers of piezoelectric transducers bonded to shape memory alloy layers using pulsed electron beams. APPROACH: This objective will be accomplished by fabricating a pulsed electron beam bonding system and investigating the beam interaction with shape memory alloys and piezoelectric materials, including the effect on materials properties and comparing this to predicted Monte Carlo calculations. PROGRESS: Contract completed. Final technical report # B199240.

Pulsed electron Beam Fabrication of Smart Materials (2)

Principle Investigator: F. M. Mako

FM Technologies Inc.

DD 1498 Work Unit Summary: 2/21/97

OBJECTIVE: Demonstrate bonding of a piezoelectric element to a shape memory alloy using the pulsed electron beam method and evaluate the piezoelectric-shape memory alloy interface. Join smart material test specimens and characterize their mechanical response to provide data that can be used by Lockheed Martin to design a needle valve for satellite propulsion that will be produced in a Phase III.

APPROACH: 1) Modify the PEB bonding system; 2) joining of piezoelectric-shape memory alloy test specimens; 3) evaluation of the interface characteristics of piezoelectric-shape memory alloy test specimens; 4) joining and evaluation of the mechanical response of smart material test specimens.

PROGRESS: No progress to report.

An Active Surface Coating for Acoustic Application

Principle Investigator: C. R. Fuller

Virginia Polytechnic Institute

DD 1498 Work Unit Summary; 22 Mar 96

OBJECTIVE: Develop an active surface treatment (i.e., an active acoustic coating) that can be applied to conventional surfaces in rotorcraft and fixed wing aircraft. APPROACH: Pursue design, analysis, and testing of three sound reduction schemes: (1) tiles comprising a PVDF actuator, a distributed thin film PVDF accelerometer, a feedback loop, and miniaturized electronics, (2) tiles including an electrostatic actuator, a tunneling accelerometer, a feedback loop, an miniaturized electronics, and (3) tiles fabricated with an adaptive foam element consisting of closed cell foam embedded with piezoelectric PVDF layers. Demonstrate the effectiveness of these various tiles by conducting noise reduction tests in a citation fuselage. Perform an analytical study of the performance of the coatings depending on the tile layout and geometry of the coated surfaces. Analyze the manufacturing aspects of the active tiles, investigating their practical production and

installation aspects, so that the selected design may lead to a successful system demonstration phase.
PROGRESS: None to report.

Semi-Active Vibration Control of Flexible Structures via Adaptive Damping and Stiffness

Principle Investigator: K. W. Wang

Pennsylvania State University

DD 1498 Progress Summary; 3/19/97

OBJECTIVE: To devise semi-active adaptive structures with suitable control algorithms to suppress structural vibrations by means of the on-line variation of the damping and stiffness characteristics of electrorheological (ER) fluid based actuators embedded in, or attached to the structure. Develop the necessary design, manufacturing, mechanics control and system integration knowledge base to facilitate the practical realization of optimal engineering semi-active structures. ... MTL is currently involved in the formulation and development of electrorheological fluids for structural applications and in vibration control techniques employing shape memory alloy materials and piezoelectric patches. **APPROACH:** Design and fabricate semi-active actuators based on the constitutive equations of electrorheological fluids. Conduct bench tests. Characterize and model the individual actuators and compare with the original design expectations. Develop intelligent and robust control algorithms for smart structures, optimizing the structure for performance. **PROGRESS:** Investigated 4 types of adaptive structure configurations using **electrorheological fluids and piezoelectric materials**; ER dampers, semi-active piezoelectric networks active-passive hybrid piezoelectric networks and active constrained layer damping treatments. New actuator concepts have been created and novel control/design methodologies have been developed. Results show that semi-active and active-passive hybrid configurations are very effective in controlling structural vibrations.

Smart Materials Structures & Mathematical Issues for Active Damage Control and Embedded Sensors for Intelligent Processing and Adhesives Monitoring.

Principle Investigator: D. J. Inman

Virginia Polytechnic Institute

DD 1498 Work Unit Summary: 12/2/96

OBJECTIVE: Develop active damage control techniques for modifying the three-dimensional strain fields in structures to improve the performance of structural systems, and assess the use of embedded sensors for information to control processes, adhesive integrity, and in-service performance monitoring. **RELEVANCE:** The active damage control research program will advance our understanding of smart material systems, and the smart adhesive research program will greatly improve reliability and quality of army materials. **APPROACH:** Develop constitutive models appropriate for macroscopic design of actuators and sensors, perform mechanical, thermal, and electrical fatigue testing of sensor and actuator materials, detailed constitutive characterization tests new actuator and sensor materials, and aging and extended life cycle tests implementation of induced strain actuators and sensors and the adaptability needed to account for extended use and aging nonlinearities. **PROGRESS:** None to report.

Growth and Differentiation of Cultured Cells on "Smart Materials" Substrates

Principle Investigator: G. G. Wallace

Wollongong University

DD 1498 Work Unit Summary: 22 Jan 1996

OBJECTIVE: to study the growth of cultured cells on conducting polymer substrates to explore the potential for controlling cell growth and differentiation. **RELEVANCE:** The research has a strong relevance to programs at NRDEC and other army laboratories in the area of smart materials. **APPROACH:** The approach will include the following: (1) determine the adhesion properties of conducting polymers of different composition and/or following pre-treatments and surface modifications. (2) characterize the electrochemical properties of the conducting polymers following the pre-treatments. (3) assess the cell viability and rate of cell growth using phase contrast microscopy and inverted microscope. (4) incorporate iodine-125 labeled nerve growth factor into the conducting polymer and effect controlled release through electrical signals to test for differentiation of PC12 (neuronal cell line) and hc3 (muscle cell line). **PROGRESS:** (Aug93-Jan96) The final report has been received and the project has terminated.

Smart Material Structures using Nonlinear Photonic Bandgap and Photon Localization for rejecting High-Intensity Laser Radiation

Principle Investigator; Y. Zhao

Wayne State University

DD 1498 Work Unit Summary: 5/6/96

OBJECTIVE: To develop a multilayered dielectric material that will reject high intensity laser radiation over a broad spectrum. **RELEVANCE:** The research has immediate application to laser protection. It may also provide a materials processing approach for the more general class of photonic bandgap materials which have broad relevance to the Army in such areas as the development of zero-threshold lasers, single mode LED's and improved planar arrays. **APPROACH:** The research will investigate a material system based on alternating polymer/polymer layers that have the same linear index of refraction (NO) but high and low nonlinear optical index, respectively. On the order of 400 layered pairs of PDMTV and 2RIU-ABPY with statistically random thicknesses will be deposited using Langmuir-Blodgett techniques. The laminated structure is expected to display a "smart" laser-protection response. At low incident intensities, the laminate will be transparent, but at higher intensity levels the material will become fully reflective of the laser light.

Fiber Optic Chameleonic Skin

Principle Investigator: M. L. Myrick

South Carolina Univ

DD 1498 Work Unit Summary: 3/13/95

OBJECTIVE: To develop a chameleonic material as a smart camouflage material. **RELEVANCE:** The Army has a continuing interest in techniques for camouflage. There are no active camouflage techniques in the visible wavelength range at this time. **APPROACH:** Research will be conducted on optical fibers coated by polymers doped with dyes. The research objectives are to: (1) develop a system to detect and redisplay an image; (2) measure the efficiency of conversion of the dyes; (3) use the displayed image to STO map the image on the fiber system; (4) measure the image produced by fluorescent dyes.

PROGRESS: None to report.

Polymer Gel Sensors and Devices controlled by Infrared Light and Ultrasound

Principle Investigator: Z. Hu

North Texas State University (Denton)

DD 1498 Work Unit Summary: 6/27/96

OBJECTIVE: To design, synthesize and characterize ultrasound and infrared-light sensitive polymer gels.

RELEVANCE: The gels under study could be actuators in smart systems with applications in robotics, medicine (drug delivery) and other systems requiring reliable, quiet actuators which can respond to infrared or other signals. **APPROACH:** 3 polymer gel systems will be studied using ultrasound as a diagnostic tool to understand the gels expansion/contraction behavior. Gels are Acrylamide, N-Isopropylacrylamide and the Polyelectrolyte. **PROGRESS:** None to report

Ferroelastic-Ferroelectric Heterostructures

Principle Investigator: J. Parise

State University of New York

DD 1498 Work Unit Summary; 3/20/96

OBJECTIVE: To design, characterize, and develop ferroelastic-ferroelectric heterostructures suitable for active suppression of both acoustic mechanical vibrations propagating at acoustic velocities and shock waves. **RELEVANCE:** This research will generate the expertise needed in the design and fabrication of smart structures relevant to Army needs in defense against air blast and shock damage.. **APPROACH:** PZT-NITI-PZT Heterostructures will be made by depositing PZT layers on commercial NITI foils using sol-gel techniques. The response of these heterostructures to fast moving transient stress waves will be examined by vibration and shock testing. Shock waves will be generated by using a cavitation-erosion set-up controlled by a variable frequency oscillator or by using a high fluence (3KW) chopped optical radiation focused onto the structure. The data on damping ability of TINI will be used to model and design a smart blast panel consisting of a NITI layer coupled with an actively controlled actuator PZT layer. The electrical response of the smart panel to a known calibrated stress wave will be determined and correlated with the design of the smart heterostructure. **PROGRESS:** None to report

Ionic Polymeric Gels as Smart Materials and Artificial Muscles

Principle Investigator: M. Shahinpoor

New Mexico University

DD 1498 Work Unit Summary: 6/27/96

OBJECTIVE: To formulate, characterize and develop synthetic muscles using ionic polymer gels.

RELEVANCE: Large motion actuators, controlled electronically by a computer and operating silently without gears and motors could find many applications in Army military systems; e.g., exoskeleton movement, stealth operations, rapid positioning for fire control, smart boots and gloves and aerodynamic and dynamic control of structures. APPROACH: The electrodynamic response of polyacrylonitrile (PAN) fibers in various geometrical forms will be studied as a function of PH and Electric field stimulations.

Theoretical modeling will support experimental developments. A number of large motion actuators will be conceptualized, designed and characterized. PROGRESS: none to report.

Active Constrained layer Damping

Principle Investigator: A. M. Baz

Catholic Univ of America

DD 1498 Work Unit Summary: 6/22/97

OBJECTIVE: To develop a new class of actively controlled constrained layer damping treatments with a high damping to weight ratio that are capable of effectively damping the vibration or the noise radiation from critical flexible structures, such as stationary and/or rotating beams and plates. RELEVANCE: The development of smart structures that feature actively controlled damping treatments will lead to the ability to realize vibration suppression and noise reduction in homogeneous and composite structures that serve as components in rotorcraft, land vehicles, and weapon systems. The result of this research will be of potential value to the missions of the Aeroflightdynamics Directorate, the Vehicle Structures Directorate, and the Army Research Laboratory (Picatinny Arsenal). APPROACH: Derive the differential equations of motion and associated finite element models that describe the operation of the active, constrained layer damping treatments. Monitor the storage and loss moduli of the actively controlled constrained layer damping treatments at different operating temperatures and excitation frequencies. Devise optimal control strategies for the active constrained layer damping treatments. Experimentally evaluate the effectiveness of the active constrained layer damping treatment in controlling the vibration of stationary beams and rotating beams and plates. Develop a software package to simulate the performance with active constrained layer damping treatments of different configurations powered with various control strategies. PROGRESS: (Jun, 1993 to May, 1996) ..., Active constrained layer damping (ACLD) treatments of vibrating structures have been developed at the Catholic University. In these treatments, *visco-elastic damping layers are sandwiched between two piezoelectric layers* to provide built-in sensing and control capabilities that actively tune the shear of the visco-elastic layers. In response to the structural vibrations, the ACLD treatments are used to control the vibration of beams, plates and cylindrical shells. The treatments are also used to control the sound radiation from plates into acoustic cavities. The studies presented include theoretical modeling and experimental testing of the ACLD treatments which demonstrate their effectiveness in controlling the vibration and noise radiation of structures.

Smart-wall for control of the Burst Cycle of Longitudinal Vortices in Turbulent Boundary Layers

Principle Investigator: Corke, T.C

Illinois Institute of Technology

DD 1498 Work Unit Summary: 2/14/97

OBJECTIVE: To develop a "smart-wall" through the integration of *optical-sensor pressure transducer* arrays and *miniature magnetic actuator arrays* into a *single wall substrate* to control transitional and fully turbulent boundary layers. RELEVANCE: The development of smart structures to control the aerodynamic flow over helicopter rotorblades is the objective of the ATCOM HACR Initiative.

APPROACH: The pressure transducer array will correspond to one mirror of an interferometer composed of a flexible silvered polyester sheet. This sheet will cover an array of small closely spaced holes in the wall surface. Fast response actuators will consist of fine wires embedded in the polyester sheet. Below the wires, in the wall surface, miniature high strength magnets (Neodymium-Iron-Boron) will cause the wires to deflect in the wall-normal and transverse directions. This sensor/actuator array will be part of an adaptive control system that utilizes a neural network architecture. PROGRESS: None to report.

Intelligent Materials & Structures Based on Ordered Assemblies of DNA and Proteins Incorporated within Electroactive Polymeric LB Monolayer Systems

Principle Investigator: K. A. Marx

Univ of Mass - Lowell

DD 1498 Work Unit Summary: 10/22/96

OBJECTIVE: To create novel ordered structures possessing unique integrated intelligent properties which may function in response to their environment in much the same way that specific proteins and DNA do in cells, and yet providing approaches to their interfacing to advanced systems via their electronic and/or optical characteristics. **RELEVANCE:** This research represents an attempt to generate a novel class of biologically derived intelligent materials by combining two separate classes of ordered assemblies in such a way that their functions are integrated to produce a unique complex materials capable of sensing and responding to its environment. As such, it is highly relevant to Army interest in smart materials.

APPROACH: Langmuir-Blodgett (LB) trough technology will be used for characterization and optimization of the general utility of Steptavidin - biotin lipid attachment strategy for complexing biologically {smart, macromolecules, e.g. DNA, proteins, to monolayer films which will then be applied toward fabrication of systems possessing hierarchical order and exhibiting novel intelligent properties. **PROGRESS:** (Mar 91 - Jul 95) New ways in which biological macromolecules could be interfaced with conducting polymers and other types of immobilization matrices were investigated. The object was to create new classes of signal transducing biomaterials that could be used in the design of intelligent materials incorporating DNA; the photodynamic proteins: the phycobiliproteins and bacteriorhodopsin; and the enzymes alkaline phosphatase, horseradish peroxidase, laccase, glucose oxidase and alcohol oxidase. The researchers have interfaced these biological macromolecules with: the conducting polymers polypyrrole and biotinylated alkylpolythiophenes of varying alkyl chain and biotin spacer lengths (using the classical biotin-streptavidin interaction), in Langmuir-Blodgett monolayers, thin film and electrochemically synthesized thick films; optical fiber surfaces by hydrophobic polymer attachment and crosslinking to silanized surfaces. And through entrapment in the cavities of Sol-Gels during their polymerization process. The researchers utilized these interaction and immobilization strategies to create monolayer thick phenolic and aniline based polymers on the LB trough surface by enzymatic polymerization. Proof of principle has been established for a second harmonic generation based all-optical memory using bacteriorhodopsin. Additionally, concentrations of Zn(II), Be(II), Bi(II) were measured in the PPB to PPM range and organophosphorus based pesticides were detected down to the hundreds PPB range.

Analysis & Optimization of Elastic Materials

Principle Investigator: R. Rostamian

Maryland University Mathematics & Statistics

DD 1498 Work Unit Summary: 1/23/96

OBJECTIVE: To investigate wave propagation in stratified elastic and viscoelastic materials and to obtain optimization (in minimal energy absorption, for example) by selecting properly material design parameters. **RELEVANCE:** This proposal is a direct response to DOD fy89 URI program announcement in the area of "smart materials and structures". **APPROACH:** Theory of homogenization will be used to obtain macroscopic material parameters from its microscopic constituents. Dynamic equations will be formulated and solved in terms of stress waves in anisotropic media. **PROGRESS:** (Sep 89 to Aug 94) the objective of this research was to investigate the propagation of waves in stratified elastic media. The focus was on the design of elastic coatings which due to their layered nature deflect the incident energy of the waves and therefore can affect the reflectivity properties of solid surfaces in interesting ways. The major result of the investigation was that it is possible to eliminate reflected waves of a prescribed bandwidth from a solid object completely.

Novel Electroactive Polymers and Block Copolymers

Principle Investigator: I. Kahn; Clark Atlanta Univ;

Principle Investigator: E. Mintz; Atlanta Univ Center Inc

DD 1498 Work Unit Summary: 8/11/94

OBJECTIVE: To prepare and characterize novel microphase separated mixed (ion-electron) conducting block copolymers and to develop an understanding of the morphology-property relationship in these polymers. **RELEVANCE:** This proposal was submitted in response to the fy89 DOD announcement for the university research initiative, research initiation program and the army's special interest area of smart

materials and structures. **APPROACH:** Anionic "living-polymerization" techniques will be used to prepare polymers such as poly(-methoxyoctaxyethylenemethacrylate-block-acetylene). The polymers will be doped with lithium perchlorate and iodine to establish their electrical properties. Characterization will include molecular weights, thermal and mechanical properties, electron microscopy, and conductivity studies. **PROGRESS:** (Aug 89 - Aug 93) Synthesis, characterization and properties of microphase separated mixed (ionic and electronic) conducting or MIEC block copolymers are reported. Poly(omega-methoxyocta-(oxyethylene) methacrylate-block-4-vinylpyridine), abbreviated as p(mg8-4vp), and poly(3-methylthiophene-block-omega-methoxyocta (oxyethylene) methacrylate) abbreviated as p(3mt-mg8), have been synthesized. Both block copolymer series may be appropriately doped to generate separate electronic and ionic conducting microdomains in the overall solid matrix. Also, highly ionic conductive solid polymer electrolytes have been prepared by blending poly(ethylene oxide), poly(2- or 4-vinylpyridine) and liClO₄. All blends were prepared by the solution blending process. Optimum blend compositions have been determined such that dimensionally stable elastomeric materials with ionic conductivities around 1.0×10^{-5} s cm⁻¹ at 25C are obtained.

Damage-Survivable & Damage-Tolerant Laminated Compoiste with Optimally Placed Piezoelectric Layers

Principle Investigator: S. P. Joshi

Texas University - Arlington Aerospace Engineering

DD 1498 Work Unit Summary: 8/13/93

OBJECTIVE: To produce a smart laminated composite structure by embedding piezoelectric sensors and actuators in it, determining the optimal placement of piezoelectric layers in a laminated composite and the durability (fatigue loading) and survivability (impact loading) of embedded sensors and actuators. Devise means of estimating the extent of damage, locating impact damage, actively suppressing damage, and controlling structural dynamics. **RELEVANCE:** The development of the ability to enhance the durability and the damage survivability of composite structures and to suppress structural damage in an active manner has considerable potential application to the design of various helicopter components.

APPROACH: To combine analytical work with testing and controlled experimentation. Specialize the piezoelectric field equations for laminated composite plates, apply continuum damage models, and devise the active control system for the piezoelectric laminate. Perform fatigue life and low velocity impact tests. Apply existing computer cooks for the analysis of (1) composite delamination and (2) the static and dynamic response of composite laminated plates. **PROGRESS:** (Aug 89 - Dec 92) The main objective of the research is to assure that the embedded sensors/actuators in a smart laminated composite structure are damage-survivable and damage-tolerant. The research requires development of analytical and computational techniques and tools together with the experimental evaluation of smart composite structural elements. An understanding of electroelastic constitutive behavior is critical to predicting the response of a structure with embedded piezoelectric material. Research efforts in this area has produced a concise formulation of linear constitute relations that has been extended to the nonlinear case. The Composite Delamination analysis and Static and Dynamic Analysis for Composite Laminated Plates packages have been modified to incorporate piezoelectric coupling in a quasi-3d and plane stress analysis. These codes are capable of analyzing laminated composites with arbitrarily placed piezoceramic patches. Both actuation and sensing can be simulated by using these codes. Edge stresses in the vicinity of an embedded piezoceramic patch and stress distribution in the vicinity of electrodes due to an actuation electric field are obtained by using these codes. A detailed stress field in the vicinity of piezoceramic sensors in a laminated plate under impact loading is also obtained by using one of the modified codes.

Ultrafast Frequency Agile Optical Materials: Organically Doped Sol-Gel Glasses

Principle Investigator: E.L. Chronister;

California Univ - Riverside

DD 1498 Work Unit Summary: 1/18/93

OBJECTIVE: To understand the basic processes of energy transfer between organic chromophores and a host transition-metal glass that undergoes a thermochromic transition. Use this knowledge to develop new nonlinear optical materials. **RELEVANCE:** This research will contribute significantly to the development of nonlinear optical devices for advanced communications, data processing and target acquisition systems. An immediate application that could have a major impact on army needs will be as smart windows (or goggles) for laser protection. **APPROACH:** The photochromic response of transition-metal oxide glasses

containing dilute dopants of organic chromophores will be studied. Sol-gel processing techniques will be used to prepare the doped glasses. Coupling of the ultrafast energy relaxation processes of the chromophores to the electronic properties of the host glass will be characterized using picosecond and subpicosecond laser-probe techniques. The effects of materials processing on the photochromic response of these glasses will be studied. PROGRESS: (Aug 89 - Aug 92) The final report, ARO 27185.5-ms-sm focuses on organically doped Sol-Gel glasses as novel fast response photochromic materials. In particular, time-resolved spectroscopic measurements of: 1) nanosecond optical energy transfer in organically doped glasses; 2) investigation of the spatial distribution of chromophores within the porous Sol-Gel matrix; 3) homogeneous dephasing of optically excited states as a probe of chromophore-host interactions; 4) time-resolved anisotropy measurements as a probe of chromophore dynamics in porous Sol-Gel matrices; and 5) optical limiting based on fast photophysical processes of organic chromophores. Optical energy transfer in organically doped Sol-Gel glasses is investigated by time-resolved fluorescence depolarization measurements. Researchers observe nanosecond optical energy transfer and analyze these results in terms of the spatial distribution of chromophores in doped porous xerogel glasses. Time-resolved polarized emission results are also used to probe the rotational dynamics of chromophores during the fabrication process from solution to gel to porous glass. Furthermore picosecond photon echo measurements have been used to obtain the homogeneous dephasing rate of organic dopants in an inorganic Sol-Gel glass, as a means of probing chromophore-host environment.

Smart Electromagnetic Structures - A New Approach to Smart Structures

Principle Investigator: M. H. Thursby

Florida Inst of Tech - Space Res Inst

DD 1498 Work Unit Summary: 6/3/1993

OBJECTIVE: To investigate active techniques for the latering of radiation and reflection characteristics of surfaces to change their radar signature. RELEVANCE: This proposal was submitted in response to the fy89 DoD announcement of the university research initiative, research initiation program and the army's special interest area of smart materials and structures. APPROACH: The approach will utilize an array of microstrip antenna elements designed such that its electrical characteristics can be changed in response to a received signal. Adaptive properties of the smart surface will be adjusted through the use of neural networks that can be trained to respond to certain signals. PROGRESS: (Aug 89 - Aug 92) The main goal in this program was to determine the feasibility of a neural network controlled antenna and to quantify the ability of the antenna and then to learn to tune automatically to the center frequency of a received signal. These goals were achieved as well as a spin-off of neural networks that have application of radar and communications systems. Because of its self adaptability the closed loop neural control of an antenna element, provides the potential for design of an easily manufacturable antenna which is immune to typical siting problems, and is tolerant to moderate external damage.

Electrorheological Fluids: A Structural Approach to Mechanisms

Principle Investigator: M. T. Shaw;;

Connecticut University - Storrs Chem Eng

DD 1498 Work Unit Summary: 1/15/93

OBJECTIVE: To elucidate the mechanism of the electrorheological effect through detailed rheological and rheooptical characterization of model electrorheological (ER) fluids. RELEVANCE: ER fluids have potential applications in high speed robotics and real time damping devices for controlling vibrations in structural elements in the army relevant systems, such as helicopter blades. APPROACH: Turbidity measurements will be used to probe the microstructure and correlation between the structure in the fluids and their rheological characteristics in both small strain and steady shear experiments. Threshold concentration and field strength for ER response will be determined to elucidate role of fibrillation in the ER response. The role of water in the ER effect will be studied using a specially prepared monodispersed polystyrene microspheres, with controlled hydrophilicity. PROGRESS: (Aug 89 - Jul 92) Fibrillation of the particulate phase has been widely observed in ER fluids and has been suggested as a viable mechanism for the ER phenomena. In this research, the author has investigated the roles of particulate properties such as size and shape anisotropy, dielectric constant and dielectric anisotropy and conductivity in the structural mechanism of ER fluids. Anhydrous ER fluids based on highly conjugated aromatic polymers were also developed.

Active Control of Nitinol-reinforced Smart Structural Composites

Principle Investigator: A. M. Baz;

Catholic University Mechanical Engineering

DD 1498 Work Unit Summary: 1/25/93

OBJECTIVE: To develop the ability to change the vibrational characteristics of structures fabricated from advanced composite materials in which shape memory nickel-titanium alloy (nitinol) wires are embedded to sense and control the static and dynamic characteristics of the composite structure. **RELEVANCE:** The generic research program offers the potential of accelerating the development of a new generation of advanced helicopter and rotorcraft systems, battle field robotic and ammunition supply systems, and vehicular suspensions and materiel handling systems. **APPROACH:** With a knowledge of the static, dynamic, and thermal characteristics of anisotropic nitinol-reinforced laminates establish the sensing capabilities of nitinol fibers by using them as strain gages and as acoustic wave guides to monitor the stress fields induced in the structure. Develop mathematical models to predict structural stability and the static, dynamic, and thermal response of nitinol reinforced composite beams and plates. Validate these mathematical models through experiments. **PROGRESS:** (Aug 89 - Aug 92) The rapidly growing technology of the shape memory nickel-titanium alloy (nitinol) is utilized to develop smart composite materials that are capable of adapting intelligently to internal and external excitations. The nitinol fibers are embedded into the composite matrix, at optimal locations and orientations, to sense and control the static and dynamic characteristics of the resulting smart composite. With such built in self inspecting and controlling capabilities the performance of the smart composite can be optimized and tailored, in real time, to match changes in the operating conditions. Emphasis has been placed on controlling the static, dynamic and thermal characteristics of anisotropic nitinol-reinforced beams. Furthermore, the sensing capabilities of the nitinol fibers are investigated by using them as distributed strain gages to monitor the physical and modal displacements of nitinol-reinforced composites. Finite element models are developed to predict structural stability and the static, dynamic and thermal behavior of nitinol-reinforced composite beams. The theoretical predictions of these models are validated experimentally.

Molecular Devices based on new Monolayer-Forming Systems

Principle Investigator: C. J. Eckhardt

Nebraska Univ Chem Dept

DD 1498 Work Unit Summary: 7/28/93

OBJECTIVE: The immediate objective is the synthesis of amphiphiles which will produce ordered LB films, particularly acentric ones, belonging to one of the planar space groups other than the hexagonal one that has thus far been observed. Acentric 3d space groups are necessary for properties such as second harmonic generation, ferroelectricity, piezoelectricity, and pyroelectricity. **RELEVANCE:** This proposal was submitted in response to the fy89 DoD announcement for the university research initiative, research initiation program and the army's special interest area of smart materials and structures. **APPROACH:** The initial effort will be to design amphiphiles of a structure which can be expected to form non-hexagonal LB films. LB films will be formed from the selected amphiphiles and the structure of the LB film will be determined. Later work will involve incorporating a number of functional groups into the amphiphiles. **PROGRESS:** (Sep 89 - Oct 92) The final report, ARO 27195.1-ch-sm, describes the formation of novel planar lattices formed by monolayers of new amphiphilic molecules. The rigid amphiphiles have cross-sections designed to provide two-dimensional crystals of the hexagonal, rectangular and oblique crystal classes. The packings are studied by atomic force microscopy. One amphiphile of triangular cross-section forms a hexagonal lattice. Two other amphiphiles, a tetracyclic and binaphthyl, are chiral and synthesized as racemates. The single binaphthyl amphiphile forms two commensurate lattices, rectangular and oblique, in the same monolayer. The tetracyclic amphiphile shows three phases on water and upon transfer at their respective formation pressures on mica, three phases are observed: glass-like, rectangular and oblique. The oblique phase results as a phase separation of the enantiomers as a result of spontaneous resolution in two dimensions. Atom-atom potential calculation are shown to be essential to the design and understanding of these planar lattices. The results have important implications beyond monolayer chemistry and physics for fields such as liquid crystals and biophysics.

Organic Materials that Respond to Molecules

Principle Investigator: A. D. Hamilton

Pittsburgh Univ Chem Dept

DD 1498 Work Unit Summary: 8/1/94

OBJECTIVE: To establish the fundamentals for designing organic polymers which will alter their mechanical and electrical properties when exposed to specific molecular species. Explore concepts that integrate these responsive entities into smart materials or systems. **RELEVANCE:** This research will contribute significantly to the development of materials which can be designed to respond to the presence of specific molecular species. An example of a potential application that could have a major impact on army needs would be as protective clothing against toxic gases. **APPROACH:** Three complementary approaches to constructing materials with a molecular recognition/response capability will be investigated. In one approach noncovalent copolymers will be prepared in which the noncovalent link between the two starting groups is a hydrogen bonding molecular recognition receptor-target molecule pair. In a second approach polydiacetylenes that are functionalized with artificial receptors will be prepared. The long range conjugation of the polydiacetylene backbone will be dependent on the arrangement of the pendant side groups, which are artificial receptors. The last approach is designed to elicit an electrical change from the presence of a particular molecular species. **PROGRESS:** (Mar 90 - Aug 93) Materials have been developed in which symmetry and structure are tunable by control of the molecular size of one of the partners in the A-B pair. Materials have been studied in which a reversible crosslinking agent's concentration is used to control material properties. The two systems are understood in quantitative detail.

Development of Novel Switchable Protein Surfaces

Principle Investigator: R. K. Gilpin

Kent State

DD 1498 Work Unit Summary: 2/4/94

OBJECTIVE: To develop a new range of separation and purification media based on recently developed {imprinting, techniques to form tailored ligand binding sites on immobilized proteins which can then recognize and bind specifically targeted compounds. **RELEVANCE:** This research presents an interesting concept and approach to the study of phenomena which are relevant to areas such as chemical synthesis, catalysis and chemical protection. It was submitted in response to the fy89 DoD announcement for the university research initiative, research initiation program and the army's special interest area of smart materials and structures. **APPROACH:** A number of chromatographic, spectrometric and related radiochemical experiments will be conducted in order to optimize the anchoring process and to understand the ligand binding and release mechanisms. Techniques to be used include (1) physicochemical measurements by inverse gas and liquid chromatography, (2) hydrogen isotope exchange studies, (3) conformational dynamics studies by FI-IR, Raman, and wide-line NMR spectrometry. **PROGRESS:** (Mar 90 - Jul 93) The work has focused on (1) the preparation and characterization of ligand-imprinted stationary phases (lisp) using lysozyme and bovine serum albumin immobilized on an amino derivatized silica and studies of the mechanism of ligand imprinting and binding, (2) dynamic studies of the bound protein under aqueous and near aqueous conditions in order to better evaluate differences in specific binding as well as non-specific solute interaction of the altered states, and (3) understanding the effects of hydration on the dynamic properties of dry and partially hydrated proteins (i.e. in the solid state).

Use of Shape Memory Alloy Controllers in the Robust Control of Smart Structures

Principle Investigator: V. S. Rao;

Missouri University at Rolla;

DD 1498 Work Unit Summary: 6/12/97

OBJECTIVE: To develop appropriate electrodeposition techniques for the processing of shape memory alloys characterized by ultra-fine sizes that are amenable to manufacturing processes (the preparation of layered smart structures is foreseen). Identify optimum deposition parameters for the best properties of the electrodeposited film. Establish mathematical models for phase transitions (constitutive relations). Develop robust controller design methodology for smart structures with rigid and flexible models through the use of reduced order models. **RELEVANCE:** The research program offers the potential of accelerating the development of a new generation of advanced rotorcraft systems, battle field robotic and ammunition supply systems, and vehicular suspension and materiel handling systems. The shape memory alloys based smart structures with robust control systems from the basis of effective vibration suppression systems. **APPROACH:** To build a slender, uniform beam with shape memory alloys prepared by an

electrodeposition process. Investigate the properties of sensor and actuator modes in the beam from both the static and dynamic response viewpoints. Use reduced order models and structural tailoring methods for simultaneous structure and control design of the test beam. Investigate the optimal distribution of sensors and actuators for effective control and spillover suppression. For the design of robust controllers, employ the linear quadratic Gaussian with loop transfer recovery design since it compensates for the modeling inaccuracy that typically exists in the mathematical models used. PROGRESS: (Feb 90 - Jun 93) The final report details an integrated interdisciplinary approach for designing and implementing robust controllers on smart structures. The application of shape memory alloy materials as actuators and sensors in the active control of smart structures has been investigated. A process was developed for the electrodeposition of IN-Ti alloys in a composition range where this system exhibits the shape memory effect. CU-ZN, AU-CA, and IN-CD alloy films were produced using the electrolytic techniques and their shape memory properties evaluated. To demonstrate some of the capabilities of smart structures and to determine the limitations imposed by hardware realizations, the investigators have designed and fabricated experimental test articles incorporating flexible structures with sma actuators, strain gauge sensors, signal processing circuits and digital controllers. Structural identification techniques have been employed in determining mathematical models of test articles from experimental data. A modified robust control design methodology was developed to accommodate the limited control force provided by the smart actuators. The robustness properties of closed loop structural systems were verified experimentally. Adaptive control methods were implemented. Neural network based identification and control algorithms were developed.

Actuators of Mica Layer Structures

Principle Investigator: L. Cartz

Marquette Univ

DD 1498 Work Unit Summary: 12/19/95

OBJECTIVE: To understand the mechanism for the large thermal expansion coefficients in mica. Use this knowledge to develop new high temperature actuators and sensors for application in smart structures.

RELEVANCE: This research will contribute significantly to the development of high figure-of-merit thermal actuators, pressure sensors, and shape memory materials for incorporation into smart structures with vibration dampening capabilities. APPROACH: To investigate the nature of the reversible volume expansion that occurs in micas as they are heated. The expansion process occurs as water vapor transfers from the metastable sites between the silicate layers to bubbles which form within dislocation networks at higher temperatures. Analytical electron microscopy, x-ray diffraction, thermal gravimetric analysis and dilatometry measurements will be performed to characterize the swelling properties and establish the thermal and cyclic stability of the process. PROGRESS: (Apr 94 - Aug 93) A mechanism for a thermal actuating systems depends on the anomalously high thermal expansion of some crystals with layer structures. These have reversible thermal expansion in excess of $10^{-1} \text{ }^\circ\text{C}^{-1}$; expansions of several thousand percent over a temperature range of a few hundred degrees centigrade have been reported. Stresses can be as high as .3 mpa, reversible thermal strains of approximately 5000 percent, and work densities greater than 10 mj/m^3 have been obtained. Crystals that behave in this fashion are phlogopite micas and also some intercalated graphites which expand perpendicular to the silicate or graphitic layers. Other layer structures have comparable properties. Extraneous, non-structural gases or liquids are entrapped between the layers. On increase of temperature, the separation of the layers increases, changing into a dome shaped lenticular bubble where the lateral spacing, perpendicular to the layers can expand from approximately 1 nm to approximately 10 microns, particularly at the liquid-gas phase transition. The resulting solid-gas composite expands more like a gas, with the atomic layers acting as flexible membranes. Implantation of rare gases XE, KR, AR, HE into muscovite mica of normal thermal expansion behavior produces the same anomalous thermal expansion effects. The rare gases XE and KR can be observed and identified unambiguously within the silicate layers and in the bubbles that develop, using RBS, and by low temperature electron diffraction of the solidified XE and KR.

Smart Composite Structures Featuring Embedded Hybrid Actuation and Sensing Capabilities

Principle Investigator: B. S. Thompson, M. V. Ghandi

Michigan State Univ

DD 1498 Work Unit Summary: 1/31/97

OBJECTIVE: To investigate the possibility of applying a hybridization of electrorheological fluid and piezoelectric actuator systems to accomplish in real time with minimal energy consumption the vibration

tailoring and control of beam and plate structures fabricated from composite materials. **RELEVANCE:** The generic research program offers the potential of accelerating the development of a new generation of advanced rotorcraft systems, battle field robotic and ammunition supply systems, and vehicular suspension and materiel handling systems. Some national defense programs that may also benefit from the proposed research include the strategic defense initiative, the national aerospace plane, NASA space stations, the B-2 bomber, and various weapons systems. **APPROACH:** To conduct analytical, computational, and experimental investigations of laminated composite structures featuring fiber optic sensing and hybrid actuation capabilities. Model mathematically (and verify experimentally) the constitutive characteristics of composites with embedded piezoelectric materials and electrorheological fluids, drawing on earlier work with Bingham solids and BKZ fluids. Devise optimal hybrid control strategies to (1) determine the location of distributed actuators incorporating er fluid and piezoelectric materials that maximize the control influence matrices and (2) minimize the settling, rise, and overshoot times of the structure. Use fiber optic sensors to perform the strain measurements needed in the control algorithms to complement the actuation system provided by the ER fluid domains and the piezoelectric materials. **PROGRESS:** (Apr 90 - Mar 94) The research focused upon the creation of engineering materials that mimic some of the attributes of naturally occurring biological materials. This was accomplished by blending different combinations of actuators, sensors, microprocessors and control algorithms in host composite materials. Comprehensive theoretical, experimental and computation investigations were undertaken and the resulting methodologies applied to a diverse group of engineering systems including beams, plates, linkages and robots.

Photo-signal Transduction in Motile Ciliate Blepharisma

Principle Investigator: P. Song

Univ of Nebraska

DD 1498 Work Unit Summary: 9/18/96

OBJECTIVE: To investigate the structure-function of the photosensor molecule, blepharismmin, involved in light-signal transduction in the unicellular motile ciliate, blepharisma japonicum. **RELEVANCE:** This unique "visual" sensory system possesses both light intensity and wavelength sensing mechanisms complete with amplification and motor response transduction events which strongly qualify as "smart materials" qualities. **APPROACH:** Blepharismmin visual pigment protein will be isolated and characterized. The role of proton release from the excited state as an initial sensory signal will be tested, as will the role of calcium ions in triggering a ciliary beat reversal. **PROGRESS:** (Feb 91 - Feb 95) The photosensing processes in stentor coeruleus and blepharisma japonicum can be described within the photo-signal transduction cascade shown above, with stentorin and blepharismmin serving as the photosensor molecules, respectively. In the photophobic responses of these ciliates, light signal (red wavelength light and intensity gradient) is perceived by the photosensor molecules localized in the pigment granule. A signal transduction then leads to the reversal of the direction of ciliary beating that is entailed in the stop turning motion of the cell away from the source of light. The final report, ARO 28748.24-ls-sm, briefly describes the photosensory transduction which utilizes stentorin and blepharismmin as the photosensor molecules.

Development of Smart Piezothermoelastic Laminae: Theory and Applications

Principle Investigator: H. S. Tzou

Univ of Kentucky

DD 1498 Work Unit Summary: 12/19/95

OBJECTIVE: (1) develop a piezothermoelastic lamination theory for multilayered composite shells (each layer of which can be either elastic, piezoelectric, thermoelastic, or piezothermoelastic); (2) devise a new finite element to analyze a distributed modal sensor actuator theory; and (3) conduct a theoretical and experimental validation of prototype structures, with one or more piezoelectric layers serving as a distributed sensor and another layer serving as a distributed actuator. **RELEVANCE:** The development of smart structures that consist of multilayered composite shells with embedded piezoelectric sensors and actuators offers the potential of suppressing structural vibrations and reducing the noise occurring inside rotorcraft constructed with these materials. The results of this research are relevant to the mission of the Aerostructures Directorate. **APPROACH:** Derive the coupled equations of motion, heat conduction, an electrodynamics for a layered piezothermoelastic continuum, including transverse shear deformation effects. To model a smart structure, develop piezothermoelastic quadratic and cubic serendipity,

Lagrangian, C Mindlin shell elements, taking care to avoid "mesh locking" due to transverse shear and membrane terms. Investigate piezothermoelastic dynamic behavior with and without feedback control based on the concepts of constant gain feedback control and constant amplitude feedback control. Test experimentally a shell composed of flexible plexigals and several stripe paired actuators with different length and/or thickness to control localized deformation and compare results with theoretical predictions. PROGRESS: (Mar 90 - Aug 94) Active "smart" structures with self-sensation, action and reaction capabilities can lead to a major technology breakthrough for the next-generation high-performance structures and mechanical systems. This new emerging area encompassing sensors, actuators, electromechanical systems, active materials, control, and structural continua can be defined as the structure-electronics - structronics. Among the commonly used sensor/actuator materials, piezoelectric materials possess unique electromechanical properties (the direct and converse piezoelectric effects) which can be respectively applied to sensor and actuator applications. The main objective of this research is to study the multi-field piezothermoelastic phenomena of piezoelectric laminae and to investigate the thermal effects to the performance of distributed piezoelectric sensors and actuators. There are three research components: 1) to develop new generic piezothermoelastic shell lamination theories, 2) to formulate piezothermoelastic finite elements and associated sensing/control numerical capabilities, and 3) to validate analytical and/or finite element solutions via laboratory experiments.

Electrical and Electronic Properties of Self-Assembled Lipid Bilayers

Principle Investigator: H. T. Tien

Michigan State Univ

DD 1498 Work Unit Summary: 10/23/95

OBJECTIVE: To elucidate the mechanisms associated with electronic processes and redox reactions in ultrathin lipid membranes containing a variety of organic conductors and redox proteins; study energy transduction and biosensing capability of newly developed self-assembled lipid bilayers. RELEVANCE: The potential contributions of this research to progress in our understanding of complex membrane system function at the molecular level have far reaching implications for the army's program in "smart materials". APPROACH: Membrane biophysics methods, including photoelectrospectrometry and cyclic voltammetry, will be used to: (1) investigate the nature and mechanisms of charge carrier generation, transport, redox reactions and energy transduction pertinent to membrane bioenergetics; (2) isolation and analysis of specific biomembrane systems reconstituted with lipid bilayers and their modification. PROGRESS: (Apr 91 - Jul 94) Cell membranes play a pivotal role in signal transduction and information processing. This is owing to the fact that most physiological activities involve some kind of lipid bilayer based receptor-ligand contact interactions. There are many outstanding examples such as ion sensing, antigen-antibody binding, and ligand-gated channels, to name a few. One approach to study these interactions in vitro is facilitated by employing artificial bilayer lipid membranes (BLMs). The PIs have focused the efforts on ion and/or molecular selectivity and specificity using newly available self-assembled BLMs on solid support (i.e. S-BLMs), whose enhanced stability greatly aid in research areas of membrane biochemistry, biophysics and cell biology as well as in biosensor designs and molecular devices development. In the final report, ARO 28750.1-1s-sm, the current work along with the experiments done in collaboration with others on S-BLMs will be presented.

Smart Structural Composites: Piezoelectric Film Deposition on Intercalated Carbon Fibers

Principle Investigator: R. Dillon; Nebraska Univ Engineering (Mech) Dept.

Principle Investigator: N. Shaikh; Nebraska Univ

DD 1498 Work Unit Summary: 6/3/93

OBJECTIVE: To develop intelligent constitutive property in carbon fiber reinforced epoxy composite system. RELEVANCE: The concept of smart composite material with a capability of vibration control and damage assessment if demonstrated successfully can lead to composite structures such as helicopter blades, which will be superior in performance and reliability. APPROACH: Smart fibers will be developed by first optimizing the electrical conductivity of the carbon fibers through intercalation and then coating them with a thin film of piezoelectric materials, such as PZT (lead zirconate titanate), PVDF (polyvinylidene fluoride) and zinc oxide. In the second phase, the optimized fibers will be incorporated into composite specimens with least loss of mechanical properties. In this phase, the smart capabilities, including damping characteristics, active controllability and, most importantly, the monitorability of damage will be determined, and optimized. PROGRESS: (Aug 89 Jul 92) The research culminated into the feasibility of smart structural

composite materials, in which the microstructure is modified with the introduction of a piezoelectric constituent. Greater success was achieved in the sensing aspect of smart properties, enabling the material to have an inherent property of health monitoring. By sensing and quantifying elastic strain, the material can monitor its dynamic state (vibration), degradation and damage. In actuation, the material is readily suitable for active vibration control and manipulative damping. One outgrowth of the results was an active fibrous sensor, which offers a readily viable alternative to a passive fiberoptic sensor as it is marred with breakage problems. A new concept of piezoelectric emission, analogous to acoustic emission, emerged which imparts the material ability to sense stress waves. This ability can be used to locate the regions of delamination and local fractures through fabrication to operational life of structure. Techniques were developed for deposition of this piezoelectric (ZNO) film on carbon and metal fibers. Sensing and actuation properties were imparted into carbon fiber composites. The results demonstrated self-sensing of strain and damage measurement in beam and shell elements. The concept is ready for technological advancement and application.

Dimensional Self-regulating Materials

Principle Investigator: J. E. Furneaux

Oklahoma Univ

DD 1498 Work Unit Summary: 8/23/96

OBJECTIVE: To investigate quantum-confined structures which can self adjust their optical properties to maximize their absorption to incident radiation. Use this knowledge to develop a single integratable detector which self tunes to incoming radiation to provide both intensity and wavelength information.

RELEVANCE: This research will explore a new material concept which could revolutionize the IR detector and optoelectronic technologies. Such a development would have a major impact on the development of future Army communications, data processing and target acquisition systems.

APPROACH: A prototype self-adjusting material will be fabricated by depositing nanometer-scale gold wires on well-characterized GAAS substrates. The application of an adjustable voltage to pairs of wires will be used to electrostatically confine the 2D electron-gas system, effectively reducing the dimensionality of the electrons from 2D to 1D. The effects of varying the width of the electrostatically confined region, from 1000-100Å, will be studied. Optical absorption by the material should be maximized when the energy separations correspond roughly to the energy of the incident photons. Thus, by introducing a simple feedback mechanism which links the conductivity of the well to the applied potential, the material should become self-locating. That is, the material should be capable of adjusting its optical properties to maximize its absorption of incident radiation, and conversely as a detector provide both intensity (induced current) and wavelength (induced voltage) information about the incident radiation. **PROGRESS:** (May 91 - Oct 94) This was a collaborative product between the University of Oklahoma and Boston University studying the possibility of producing an infrared detector which integrates the function of a spectrometer. The successful implementation of these ideas could lead to a smart infrared detector. The system studied as a prototype is the two-dimensional electron system (2DES) GAAS-ALGAAS modulation-doped heterostructure system patterned with very narrow gates. This leads to a transition to a one-dimensional electron system (1DES). This system is expected to be particularly sensitive to infrared radiation but at the crossover from a 2DES to a 1DES. Thus this system is a dimensionally self-regulating material. Considerable progress has been made toward these goals. Successful theoretical models have been made of the proposed devices and have produced and tested the first generation devices electrically. Far-infrared tests are now in progress.

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